STUDIES ON ECOPHYSIOLOGICAL RESPONSES OF DURUM WHEAT GENOTYPES UNDER WATER DEFICIT CONDITIONS

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MALAYSIA

2010

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B.Sc. and M.Sc. (Ferdowsi University of Mashhad, Iran)

Thesis Submitted in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

Institute of Biological Sciences

Faculty of Science

University of Malaya

Malaysia

2010

DECLARATION

In the Name of Allah, the Most Gracious. the Most Merciful

I hereby declare that all the work in this thesis is the results of my own data, effort and observation and all references sited have been acknowledged. I also affirm that this thesis has never been submitted for any other degree somewhere else.

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This dissertation is dedicated to my wife, Reihaneh Shagholi and to our children, Farzaneh and Moein. Their love, support, and encouragement throughout this academic research journey have meant everything to me.

ACKNOWLEDGEMENTS

First and foremost, I thank Allah the Almighty for His grace and blessings, for giving me the spiritual inspiration to undertake this study. I would like to gratefully acknowledge the contributions of several people who have helped me to complete this study in time and make the documentation a reality. First and foremost, I would sincerely like to thank my supervisors Professors Amru Nasrulhaq Boyce and Syed Shahar Syed Ahmad Barakbah for their invaluable contribution and consistent guidance in my research and thesis. Their frequent advice, encouragement, friendly persuasion, positive work ethics and constant promptings have all spurred me to complete my thesis on time. I am greatly indebted to my supervisors in many ways. Secondly, I wish to express special appreciation and thanks to Prof. Dr. Baki Hj. Bakar, Prof. Dr. Rashed Mohasel, and Assistant Prof. Dr. Masoud Ghodsi for their valuable advice during the duration of my research. Thirdly, I wish to extend my sincere thanks and gratitude to Prof. Dr. Mohd Sofian Azirun, Dean of the Science Faculty and Head of the Institute of Biological Science (ISB) for providing a conducive working environment in ISB. Thanks are also due to other staff members of the Faculty of Science who have in one-way or another given me their cooperation, help and moral support. Fourthly, special thanks are extended to Assistant Prof. Dr. Hossain Tavakoli, Dean of Khorasan-e-Razavi Agricultural and Natural Resource Research Center and his staff for cooperating to conduct the field researches. Special thanks to Prof. Dr. Mohhamad Kafi for sharing his time and editorial expertise. I especially thank my friends and former classmates Dr. Mahdi Faravani and Dr. Abbas Fallah Toosi for their valuable advices and cooperation during our study. Last but not least, I would like to take this opportunity to thank my beloved family members for their encouragement and moral support which was so meaningful during the duration of my research and PhD study.

STUDIES ON ECOPHYSIOLOGICAL RESPONSES OF DURUM WHEAT GENOTYPES UNDER WATER DEFICIT CONDITIONS

ABSTRACT

Water is the main component in the make-up of plants and serves as the solvent, which transports minerals and dissolved carbohydrates throughout the plant. However, the ecological and physiological responses of plants to water limitation vary at different developmental stages and limits crop production and yield in crops. Therefore, investigation of the plant response to drought at its different developmental stages can be useful to overcome the negative effects of water stress in different plant growth stages. In addition, although, drought stress has been well documented as an effective parameter in decreasing crop production in arid and semi arid regions, developing and releasing new cultivars, which are adaptable to water deficit conditions can be a constructive program to overcome drought conditions. The present study was undertaken in two phases to examine the physiological, agronomical, anatomical and biochemical variations in durum and bread wheat in response to different water deficit conditions. In the first phase, twenty promising genotypes of durum wheat were tested at the Institute of Biological Sciences, University of Malaya under optimum and different osmotic stress conditions using polyethylene glycol (PEG) for ranking their osmotic stress tolerance. It was laid out in factorial experiments based on a completely randomized design (CRD) with three replications and two factors. First factor was different osmotic stresses and the second factor was different durum wheat genotypes.. In addition to this, the field experiments were laid out in split-plot arrangement based on a complete randomized block design with three replications in the Khorasan Razavi Agricultural and Natural Resource Research Center, Iran. Irrigation regimes were considered as the main plots and included four levels: I1, optimum irrigation; I2, water limitation from one-leaf to floral initiation stage; I3, water limitation from floral initiation to anthesis; I4, water limitation after anthesis up to ripening. Precipitation was prevented by using a mobile rain shelter whenever rain started. Subplots were assigned to four durum-promising lines (G1, G2, G4, and G5) and a Chamran bread wheat cultivar (G3). The results of laboratory and field experiments at different growth and development stages indicated that majority of the selected genotypes at the germination stage using PEG under osmotic stress condition showed similar behavior due to drought tolerance under different irrigation regimes at the plant establishment stage in the field condition. Different osmotic stress treatments reduced all the germination traits except root to shoot length ratio and root to shoot dry weight ratio. The highest correlation

coefficient was calculated between seedling dry weight and shoot dry weight. Furthermore, the highest and lowest values of germination stress tolerance index (GSTI) were observed in the low (-0.3 MPa) and severe (-0.9 MPa) osmotic stress treatments. Water deficit caused a reduction in physiological parameters including leaf area index (LAI), crop growth rate (CGR), relative growth rate (RGR), net assimilation rate (NAR), photosynthetically active radiation interception (PARI), radiation use efficiency (RUE), relative water content (RWC), canopy temperature depression (CTD), accumulation of dry matter, dry matter translocation efficiency to grain, leaf chlorophyll content, stomatal conductance and photosynthetic rate. In addition, morphological factors such as spikelets per spike, potential florets, spike length, spike dry weight, number of spike m^{-2}, grain per spike, plant height, day to maturity, spike partitioning coefficient (SPC), spike harvest index (SHI) and grain yield (GY) decreased under different water deficit treatments. Nevertheless, reduction in the water use efficiency (WUE) was concomitant with water limitation at the reproductive and grain filling periods. Water limitation at the vegetative phase (I2) increased 1000-grain weight (TGW), harvest index (HI), WUE and maturity duration. Furthermore, proline accumulation and contribution of pre-anthesis assimilates to the grain significantly increased under water deficit condition compared to optimum irrigation. The final results also revealed that both genotypes G2 durum wheat and G3 bread wheat were achieved the higher values for the LAI, CGR, PARI, RUE, SHI, SPC, WUE, RWC, CTD, dry matter accumulation, remobilization parameters, spike dry weight, total and fertile tillers, spikelets per spike, spike length, chlorophyll content, proline accumulation, stomatal conductance and photosynthetic rate under water deficit conditions compared to other genotypes. In addition, the study of drought tolerant and susceptible indices and their correlations with grain yield also confirmed that amongst the drought tolerant indices, which were used to estimate the highest desirable drought tolerance genotypes, the stress tolerance index (STI) exhibited better performance for screening the genotypes under optimum irrigation and different water deficit conditions. Consequently, the most tolerant genotypes related to different water deficit conditions were G3 bread wheat and G2 durum wheat genotypes, which were screened using stress susceptibility index (SSI), stress tolerance index (STI), tolerance index (TOL), mean productivity (MP), geometric mean productivity (GMP), yield reduction ratio (Yr) and relative performance (PR).

KAJIAN RESPONS ECOFISIOLOGI KE ATAS GENOTIP GANDUM DURUM DALAM KEADAAN KEKURANGAN AIR

ABSTRAK

Air adalah komponen utama tumbuh-tumbuhan dan bertugas sebagai pelarut yang mengangkut bahan mineral dan karbohidrat terlarut kepada semua bahagian tumbuhan. Walau bagaimanapun reaksi ekologi dan fisiologi tumbuhan terhadap kekurangan air berbeza, bergantung kepada peringkat perkembangan tumbersaran dan akan menghadkan pengeluaran dan hasil tanaman. Dengan demikian kajian ke atas tindakbalas tumbuhan kepada musim kemarau, pada peringkat perkembangan dan tumbersaran yang berbeza, adalah berguna untuk mengatasi kesan negatif tekanan air pada peringkat tumbersaran yang berbeza. Tambahan kepada ini, walaupun tekanan kemarau telah banyak dikaji dan dilaporkan sebagai satu parameter yang berkesan mengurangkan pengeluaran tanaman dalam kawasan kering dan separa kering, mewujud dan menggunakan kultivar baru yang boleh beradaptasi kepada keadaan kekurangan air, boleh menjadi satu program konstruktif untuk mengatasi keadaan kemarau. Kajian ini dilakukan dalam dua fasa untuk mengkaji fisiologi, anatomi dan perubahan biokimia dalam gandum durum dan gandum roti yang bertindakbalas kepada keadaan kekurangan air yang berbeza. Dalam fasa pertama, dua puluh genotip gandum durum yang menggalakkan diuji di Institut Sains Biologi, Universiti Malaya didalam keadaan osmosis optimum dan pada tekanan osmosis yang berbeza dengan menggunakan polietilena glikol (PEG), bagi menentukan toleransinya kepada tekanan osmosis. Eksperimen dikendalikan secara eksperimen faktorial berdasarkan rekabentuk rawak penuh dengan tiga replikasi dan dua faktor. Tambahan kepada ini eksperimen di ladang diletakkan dalam susunan split-plot berdasarkan rekabentuk rawak penuh dengan tiga replikasi di Pusat Penyelidikan Pertanian dan Sumber Semulajadi Khorasan Razavi di Iran. Regim pengairan dikira sebagai plot utama dan terdiri daripada empat paras: I1, pengairan optimum; I2, pengairan dihadkan pada peringkat satu-daun sehingga permulaan pembungaan; I3, pengairan dihadkan pada peringkat permulaan pembungaan sehingga antesis; I4, pengairan dihadkan selepas antesis sehingga kematangan. Hujan dihalang dengan menggunakan pelindung hujan bergerak. Subplot terdiri daripada empat baka gandum durum yang menunjuk harapan yang baik (G1, G2, G4, and G5) dan kultivar gandum roti Chamran (G3). Keputusan eksperimen dalam makmal dan di ladang pada peringkat tumbersaran dan perkembangan yang berlainan, menunjukkan kebanyakkan genotip yang terpilih pada peringkat percambahan dengan menggunakan PEG untuk tekanan osmotik, menunjukkan reaksi yang hampir sama dengan toleransi kemarau di bawah regim pengairan berbeza, pada peringkat penetapan tumbuhan di ladang. Kelakuan tekanan osmosis yang berbeza, mengurangkan ciri-ciri percambahan,

kecuali nisbah panjang akar ke pucuk dan nisbah berat kering akar ke pucuk. Koefisien korelasi yang tertinggi diperolehi antara berat kering anak benih dan berat kering pucuk. Tambahan pula nilai tertinggi dan paling rendah untuk indeks toleransi tekanan percambahan (GSTI) diperhatikan dalam kelakuan tekanan osmosis rendah (-0.3MPa) dan osmosis teruk (-0.9MPa). Pengurangan air menyebabkan penurunan dalam beberapa parameter fisiologi termasuk indeks luas daun (LAI), kadar tumbersaran tanaman (CGR), kadar tumbesaran relatif (RGR), kadar bersih asimilasi (NAR), pemintasan radiasi aktif fotosintesis (PARI), keberkesanan penggunaan radiasi (RUE), kandungan air relatif (RWC), kerendahan suhu kanopi (CTD), penggumpulan bahan kering, keberkesanan translokasi bahan kering kepada bijian, kandungan klorofil daun, konduktans stomata dan kadar fotosintesis. Tambahan kepada ini, faktor morfologi seperti bilangan spikelet se spike, potensi floret, panjang spike, berat kering spike, bilangan spike se m^{-2}, bijian se spike, ketinggian tumbuhan, hari ke matangan, koefisien pembahagian spike (SPC), indeks tuai spike (SHI), dan hasil bijian (GY), menurun dalam kelakuan kekurangan air yang berlainan. Namun demikian, penurunan dalam keberkesanan penggunaan air (WUE) turut bersama dengan pembatasan air pada peringkat pembiakan dan pengisian bijian. Pembatasan air pada peringkat vegetatif (I2) menambahkan berat 1000 bijian (TGW), indeks penuaian (HI), WUE dan tempoh kematangan. Tambahan pula, pengumpulan prolina dan sumbangan asimilat sebelum antesis kepada bijian, meningkat secara signifikan di bawah kelakuan kekurangan air berbanding dengan pengairan optimum. Keputusan akhir juga menunjukkan bahawa genotip G2 gandum durum dan G3 gandum roti memperolehi nilai-nilai yang lebih tinggi bagi LAI, CGR, PARI, RUE, SHI, SPC, WUE, RWC, CTD, pengumpulan bahan kering, parameter mobilasi semula, berat kering spike, jumlah dan tiler subur, spikelet se spike, panjang spike, kandungan klorofil, pengumpulan prolina, konduktans stomata dan kadar fotosintesis di bawah keadaan kekurangan air berbanding dengan genotip lain yang dikaji. Tambahan kepada ini, kajian tentang indeks toleransi dan mudah kena kemarau (*susceptibility*) dan korelasinya dengan hasil bijian mengesahkan bahawa di antara indeks toleransi kemarau, yang digunakan untuk menganggarkan genotip toleransi kemarau yang paling dikehendakki, indeks toleransi tekanan (STI) telah menunjukkan prestasi yang lebih baik untuk penskrinan genotip di bawah pengairan optimum dan keadaan kekurangan air. Dengan demikian genotip yang paling toleransi kepada keadaan kekurangan air adalah genotip G3 gandum roti dan G2 gandum durum yang telah diskrinkan dengan menggunakan indeks mudah kena kemarau (*susceptibility*) (SSI), indeks toleransi tekanan (STI), indeks toleransi (TOL), pengeluaran min (MP), pengeluaran min geometrik (GMP), nisbah hasil penurunan (Yr) dan prestasi relatif (PR).

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ABBREVIATIONS

BY	Biological Yield
CDM	Cumulative Dry Matter
CGR	Crop Growth Rate
CIMMYT	Centro Internacional De Mejoramiento De Maíz Y Trigo
CIMMYT	(International Maize and Wheat Improvement Center)
CL	Coleoptiles Length
CPAA	Contribution of Pre- Anthesis Assimilates to Grain
CR	Capillary Rise
CRD	Completely Randomized Design
CTD	Canopy Temperature Depression
D	Drainage
DH	Day to Heading
DMA	Day to Maturity
DMSa	Dry Matter Shoot at Anthesis
DMSm	Dry Matter Shoot at Maturity
DMT	Dry Matter Translocation
DMTE	Dry Matter Translocation Efficiency
G %	Germination Percentage
GDD	Growing Degree Days
GMP	Geometric Mean Productivity
GN	No. Grain Spike^{-1}
GR	Germination Rate
GSTI	Germination Stress Tolerance Index
GY	Grain Yield
HI	Harvest Index
I	Irrigation
I°	Incident Radiation
ISB	Institute of Biological Science
k	Light Extinction Coefficient
LAI	Leaf Area Index
LSD	Least Significant Difference
MD	Maturity Duration
MGT	Mean Germination Time
MP	Mean Productivity
NAR	Net Assimilation Rate
NPF	Number of Potential Florets Spike-^{1}
OLAI	Optimum Leaf Area Index
P	Precipitation
PARI	Photosynthetically Active Radiation Interception
PEG	Polyethylene Glycol
PI	Promptness Index
PLH	Plant Height
PR	Relative Performance
R	Run Off
RDW	Root Dry Weight
RGR	Relative Growth Rate

RL	Root Length
RQS	Reference Quantum Sensor
RUE	Radiation Use Efficiency
RWC	Relative Water Content
SDW	Shoot Dry Weight
SHI	Spike Harvest Index
SL	Length Shoot
SLDW	Seedling Dry Weight
SPAD	Soil Plant Analysis Development
SPC	Spike Partitioning Coefficient
SPDW	Spike Dry Weight
SPII	Seed and Plant Improvement Institute
SPK.L	Spike Length
SPKDW	Spike Dry Weight
SPKE	Spikelets Spike-^{1}
SPKN	No. Spike M^{-2}
SSI	Stress Susceptibility Index
STI	Stress Tolerance Index
TDMS	Total Shoot Dry Matter
TGW	1000-Grain Weight
TNT	Total Number of Tillers
TOL	Tolerance Index
TSP	Tiller Survival Percentage
TWU	Total Water Use
WP	Osmotic Potential
WUE	Water Use Efficiency
Yr	Yield Reduction Ratio
ΔW	Soil Water Content

CHAPTER 1

GENERAL INTRODUCTION

1.1 OUTLINE OF THESIS

1.1.1 Chapter 1: General Introduction and Objectives

This chapter introduces the background and sets the context for this thesis. It includes a general overview of the impact of drought stress on crop production, ecophysiological factors determining drought tolerance, the importance of adaptation to diverse environmental conditions and the nutritional importance of bread and durum wheat. In addition, the general and specific objectives are presented, as well as a brief outline of the thesis. Finally, the publications derived from this work are listed.

1.1.2 Chapter 2: Review of Literature

The second chapter covers the literature review pertinent to the topic under study. It focuses on the ecophysiological responses of durum and bread wheat cultivars to water deficit conditions at different stages of growth and development.

1.1.3 Chapter 3: Osmotic Stress-Induced Changes on Germination and Seedling Growth of Promising Durum Wheat Genotypes

This chapter focuses on the importance of seed germination and seedling growth for the successful stand establishment of the wheat plants. The drought tolerant and susceptible genotypes were screened under four levels of osmotic stress conditions, using drought stress indices in the field experiments.

1.1.4 Chapter 4: Water Deficit-Induced Changes on Physiological Traits of Durum Wheat

The fourth chapter reports the effects of water deficit on dry matter accumulation based on cumulative growth degree-days during different growth and development phases. The following growth parameters; leaf area index, crop growth rate, relative growth rate and net assimilation rate, were analyzed for both water deficit

and genotypic treatments. The relationship between photosynthetic active radiation interception, radiation use efficiency and growing degree-days were investigated under different irrigation conditions.

1.1.5 Chapter 5: Impact of Water Deficit on Remobilization of Stored Pre - Anthesis Assimilates in Durum Wheat

Chapter five describes the contribution of pre-anthesis assimilates stored in shoots in grain filling. In addition to this, the efficiency of dry matter translocation amongst the genotypes was determined in order to screen suitable genotypes in the presence of drought tolerance.

1.1.6 Chapter 6: Drought-Induced Changes on Phenotype, Yield and Yield Component of Durum Wheat Genotypes

The morphological and ecophysiological differences, brought about by the drought stress conditions are described here. In addition, parameters related to final production, such as spike partitioning coefficient, spike harvest index, tiller survival percentage, number of spike m^{-2} and grain $spike^{-1}$, 1000-grain weight, plant height, day to maturity and maturity duration assay under different irrigation regimes are reported.

1.1.7 Chapter 7: Application of Physiological and Biochemical Indices for Screening of the Drought Tolerant Durum Wheat Genotypes

Chapter seven reports the leaf relative water content, canopy temperature depression, proline concentration, chlorophyll content, stomatal conductance and photosynthetic rate due to the different irrigation regimes at the booting, anthesis and soft dough stages, in the different genotypes studied.

1.1.8 Chapter 8: General Discussion and Conclusions

The last chapter deals with the main discussion points and conclusions drawn from this study.

1.2 GENERAL INTRODUCTION

1.2.1 Importance of Drought Stress in Crop Production

Mankind is totally dependent on crops for most of his food, as well as for many other important needs. Currently crops occupy nearly one fifth of the planet's vegetated surface, by far the biggest imprint of man upon the planet and its landscapes. Cropping is also the world's largest source of employment and livelihood, with well over 1 billion small farmers in developing countries. On the other hand, water is the most important molecule in all living organisms as well as plants and its shortage can limit crop production. Whater is essential in terms of plant functioning through turgor maintenance; assimilate translocation, nutrient transport, transpiration, its involvement in reactions. Therefore, monitoring plant water status was probably the first plant physiological work carried out (Chauki *et al.* 2003; Vasil 2003; Costa *et al.* 2004; Dai and Li 2004; Casati and Walbot 2004).

Water drives agricultural production in many parts of the world. Indeed, one of the main factors behind the successful increase in crop production due to 'Green Revolution' was the increased use of irrigation. However, in the 21st century, increasing water demand by industry, urban populations and environmental flaws and reduction in water quality will reduce the water available for irrigated agriculture. Moreover, emerging climate change is predicted to reduce rainfall and increase rainfall variability in many agricultural systems (Wang and Li 2000; Erdei *et al.* 2002; Anand *et al.* 2003; Zhao *et al.* 2003; Chen and Gallie 2004; Dai and li 2004; Jiang and Ren 2004).

Water stress in plant life is common and occurs widely in nature. It occurs whenever water absorption by the plant is lower than the transpiration from the leaves to the atmosphere. It has the potential to seriously affect crop production in arid and

semi-arid regions, where many developing and under-developed countries accommodated in this category. In these regions, during drought period water potentials in the rhizosphere become sufficiently negative and reduce water availability to sub optimal levels for plant growth (Ashraf *et al.* 1996). Hence, the understanding of the physiological and the genetic adaptive mechanisms controlling drought tolerance has been a crucial aspect in plant biology and ecology. Plant response to drought can be studied by the identification of traits that bear relationship with drought tolerance at the morphological, physiological, cellular, biochemical and molecular levels. Consequently, the study of the diversity of drought tolerance mechanisms can provide useful information on the different possibilities of adaptation to water scarcity (Larbi and Mekliche 2004; Addaa *et al.* 2005).

1.2.2 Wide Adaptation of Wheat to Diverse Environmental Conditions

Wheat is the dominant crop in temperate countries being used for human food and livestock feed. It is a widely adapted crop which is grown in temperate, irrigated to dry and high rain-fall areas and in warm, humid to dry and cold environments. Undoubtedly, this wide adaptation has been possible due to the complex nature of the plant's genome, which provides great adjustability to the crop (Acevedo *et al.* 2002, Shewry 2009). It is the staple food for more than 35% of the world's population and has accompanied humans since ancient times in their evolution and development, evolving itself from its primitive form (emmer wheat) into the presently cultivated species. The most important modern wheat species now are the hexaploid bread wheat and the tetraploid durum wheat, which are distinctive based on their genomic number, grain composition and food end-use quality attributes. Except for the very warm tropics, high humidity, wheat adapts to all diverse climatic conditions prevailing in agricultural lands and is harvested in the world all year around. Its wide adaptation to diverse

environmental conditions, along with its unique characteristic of possessing a viscous elastic storage protein complex called gluten, makes wheat one of the most important food crops in the world (Pena 2002; Shao *et al*. 2006).

Wheat is counted among the 'big three' cereal crops, with over 600 million tons (m tons) being harvested annually. The total world harvest in 2007 was about 607 m tons compared with 652 m tons of rice and 785 m tons of maize. Approximately 90 to 95 percent of the wheat produced in the world is common wheat, which is better known as hard wheat or soft wheat, depending on grain hardness. The average area planted for durum wheat is about 18 million hectares (m ha) with production averaging about 30 m tons annually, or 5%, of global wheat production. Of these, about 35% is produced in North Africa and West Asia, 25% in North America, 30% in the EU, and 10% in India. Most durum wheat production is based on spring varieties (International Grains Council 2002; USDA 2005; Dixon *et al*. 2009; Shewry 2009).

1.2.3 Bread and Durum Wheat Botany

Bread Wheat, scientifically named as "*Triticum aestivum*" belongs to the plant family of Poaceae. As shown in Fig. 1.1, the *Triticum* genus has several species, commercially different with different growth habits and spike or grain structure. The number of chromosome is an important issue and based on the number of chromosomes, a wheat genus will be diploid (AA), tetraploid or hexaploid (Kirby, 2002). For example bread wheat is hexaploid (AABBDD) whilst durum wheat is allotetraploid (AABB) with 28 chromosomes (2n= 4x = 28), containing the full diploid complement of chromosomes from each of its progenitor species (Wall *et al.* 1971; Bozzini 1988; Feldman 2001; Shewry 2009).

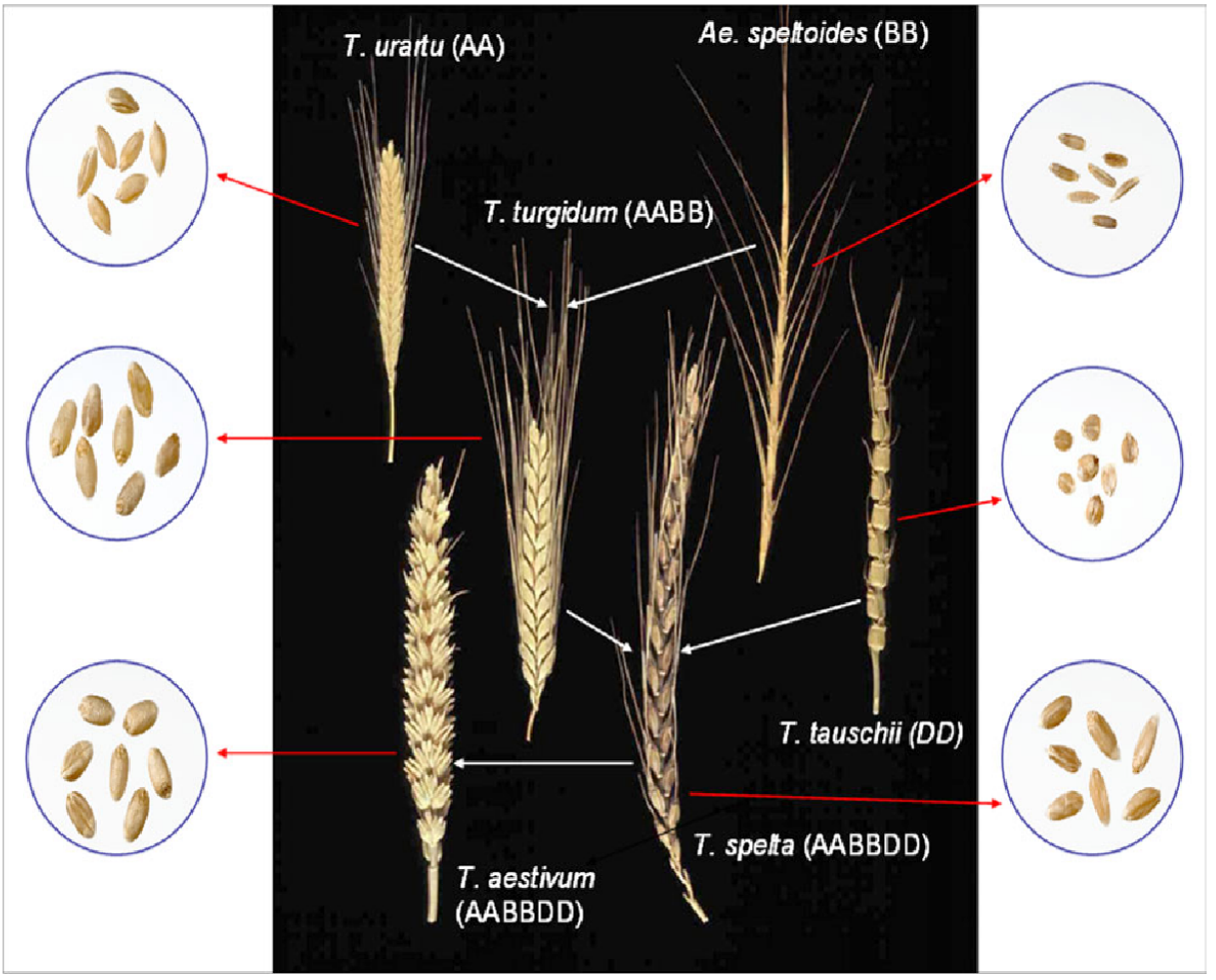

Fig. 1.1. The evolutionary and genome relationships among cultivated bread and durum wheat and related wild diploid grasses, showing examples of spikes and grain (Shewry 2009).

Durum wheat (*Triticum turgidum durum*) is a monocotyledonous plant of the poaceae family and Triticeae tribe and belongs to the genus *Triticum*. For commercial production and human consumption, durum wheat is the second most important *Triticum* species, next to common wheat (Canadian Food Inspection Agency 2006). Durum wheat is a mid-tall annual grass with flat leaf blades and a terminal floral spike consisting of perfect flowers. As with common wheat, there are durum wheat varieties that have a semi-dwarf structure. The grain of wheat is a dry indehiscent fruit. The embryo or germ is situated at the point of attachment of the spikelet axis, and the distal end has a brush of fine hairs. The embryo is made up of the scutellum, the plumule (shoot) and the radicle (primary root). The scutellum is the region that secretes some of the enzymes involved in germination and absorbs the soluble sugars from the breakdown of starch in the endosperm. The root system is composed of seminal roots, which are produced by the young plant during germination, and adventitious roots, which arise later from the basal nodes of the plant to become the permanent root system. The stem is cylindrical, erect, usually hollow, and subdivided into internodes. Some durum wheats have solid stems (Bozzini 1988; Clarke *et al.* 2002 and Kirby 2002). Culms (tillers) arise from auxiliary buds at the basal nodes of the main stem. The number of culms formed depends on the variety, growing conditions, and planting density. Under usual field conditions, a plant may produce three culms in addition to the main shoot, although not all will necessarily produce grain (Bozzini 1988).

As with other grasses, durum wheat leaves composed of a basal portion (the leaf sheath) which envelops the stem, and a terminal portion, which is linear with parallel veins and an acute apex. At the attachment of the leaf sheath is a thin, transparent membrane (ligules) with two small lateral appendix called auricles. The main stem and each culm produce a terminal inflorescence. The inflorescence of durum wheat is a spike with a rachis bearing spikelet separated by short internodes. Each spikelet consists

of two glumes (bracts) enclosing two to five florets, all borne distichously on a racially. Each floret is enclosed by bract like structures called the lemma and the palea. Each floret is a perfect flower, containing three stamens with bilocular anthers and a pistil bearing two styles with feathery stigmas. Mature pollen is fusiform; normally containing three nuclei. Each floret has the potential to produce a one-seeded fruit called a caryopsis. Each seed contains a large endosperm and a flattened embryo located at the apex of the seed and close to the base of the floret (Bozzini 1988; Nelson *et al.* 1995; Kirby 2002).

1.2.4 Nutritional Importance of Wheat

The relative importance of wheat as a staple food in selected countries is displayed in Appendix 4. Wheat provides 500 kcal of food energy per capita per day in the two most populous countries in the world, China and India, and over 1,400 kcal per capita per day in Iran and Turkey. Overall, across the developing world, 16% of total dietary calories come from wheat (26% in developed countries), which is second only to rice in importance. As the most internationally traded food crop, wheat is the single largest food import in developing countries and a major commodity in emergency food aid (Dixon *et al.* 2009).

Durum wheat has the hardest grain of all wheats and is used to make semolina, a coarse granular flour produced during the milling of fine flour. With its strong gluten properties and superior cooking characteristics, semolina is used in pasta products such as macaroni, and spaghetti. In some countries, durum wheat is preferred for the production of couscous and bulgur, two well known Middle Eastern dishes. Traditional breads are also made with durum flour. Durum wheat is the preferred wheat for pasta products due to its excellent amber color and superior cooking quality (Pitz 1992).

Historically durum wheat has received insufficient attention from breeders and farmers. Even in areas with low rainfall, farmers prefer to cultivate bread wheat, which relegates durum wheat cultivation to more marginal areas. It can be due to insufficient suitable durum wheat seeds compared to bread wheat for planting in different environmental conditions. In addition to this, durum wheat mostly is used as pasta products. Therefore, it is nessesary to develop the pasta factories and mashinaries. Despite its importance for human consumption and diet, little progress has been made with regard to durum wheat yield improvement in dry areas. One of the best options for crop production, yield improvement, and yield stability under soil moisture deficient conditions is to develop drought tolerant crop varieties. Hence, developing crops that have an advantage under abiotic stress conditions is a major challenge for durum wheat improvement programs (Begg and Turner 1976; Siddique *et al.* 2000). Varietals differences in drought resistance have been reported in wheat (Steiner *et al.* 1990), which can be further exploited by appropriate breeding programs to develop new varieties with more ability to withstand cultivation in arid regions of the globe.

1.3 OBJECTIVES

1.3.1 General Objectives

In the present study, the ecophysiological parameters of durum and bread wheat genotypes were studied based on germination and seedling characteristics under laboratory as well as field conditions. The growth parameters analyzed included: plant dry matter accumulation and translocation, intercepted photosynthesis active radiation, radiation use efficiency, remobilization of wheat, tillering and spike traits, yield and yield components, harvest index, water status and stomatal regulation capacity, canopy temperature, leaf chlorophyll content and proline accumulation and the photosynthetic rate. All these ecophysiological parameters were analyzed under conditions of different degrees of water availability at different growth and development stages except germination. Germination was analyzed under different osmotic stress conditions using different concentrations of polyethylene glycol (PEG). The general objectives of the present work were:

1.3.2.1 To study the effects of water deficit on different stages of growth and development in different durum and bread wheat genotypes

1.3.2.2 To analyze drought tolerance of different genotypes by looking at its ecophysiological traits

1.3.2.3 To compare the performance of wheat genotypes under osmotic stress conditions in the laboratory and water deficit induced conditions in the field

1.3.2 Specific Objectives

1.3.2.1 To determine the germination sensitivity threshold in promising durum wheat genotypes

1.3.2.2 To study the growth parameters, physiological traits and accumulation of dry matter under different irrigation regime

1.3.2.3 To determine the intercepted photosynthetic active radiation and radiation use efficiency in the genotypes studied at different growth and development stages

1.3.2.4 To monitor the tillering behaviors and spike characteristics related to drought tolerance

1.3.2.5 To compute the yield and yield components of the durum and bread wheat genotypes under different water deficit condition

1.3.2.6 To identify the appropriate screening tools for drought tolerance using relatively physiological parameter

1.3.2.7 To elucidate the relationship between the ecophysiological traits and grain production using correlation coefficients

CHAPTER 2

REVIEW OF LITERATURE

2.1 REVIEW OF LITERATURE

2.1.1 Drought Resistance Mechanisms

Drought is a complex physico–chemical process, in which many biological macromolecules and small molecules, such as nucleic acids, proteins, carbohydrates, lipids, hormones, ions, free radicals, and mineral elements are involved. In addition, response to drought stress may involve metabolic and structural changes that improve plant functioning under stress. Furthermore, it can cause some alternates in root to shoot ratios, leaf anatomy, and temporary accumulation of reserves in stem, carbon and nitrogen metabolism. It has been revealed that in durum wheat the degree of resistance to water stress at the plant level depends on the existence of a mechanism operating at the cellular level (Bohnert and Sheveleva 1998; Bajji *et al.* 2000; Pinheiro *et al.* 2001; Chartzoulakis *et al.* 2002; Bartel and Bartel 2003; Halford and Paul 2003; Maathuis, *et al.* 2003; Yordanov *at al.* 2003; Andersson *et al.* 2004; Casati and Walbot 2004; Dhanda *et al.* 2004; Jiang and Zhang 2004; Jones-Rhoades and Bartel 2004).

The adaptation strategies of plants to drought stress include drought escape, avoidance and tolerance. Among those, drought escaping causes completion of the plant life cycle before beginning of the drought period. Also, water stress avoidance include the maintenance of the plant water status in the presence of drought stress, while drought tolerance involves maintenance of the plant function in the presence of drought. In additionto this, the ability of drought tolerance in the plants to cope the partial dehydration of its own tissues. Different plant strategies to cope with drought, normally involve a mixture of stress avoidance and tolerance strategies that varies with the genotype (Levitt 1980; Turner *et al.* 2001; Chaves *et al.* 2002).

Exploring physiological mechanisms of drought resistance for different wheat genotypes has been known to find new drought resistance gene resources. In addition, it has been used as a basis for wheat drought resistance biotechnological breeding (Araus *et al.* 2002; Shao *et al.* 2006). On the other hand, shortening of the crop growth duration has been a very successful breeding approach in very poor environments for Mediterranean conditions. However, selection for morphological and physiological components of drought resistance in the early stages of a breeding program may give information when yield is not available. However, selection of drought tolerance varieties based on grain yield in the breeding programs may introduce characters with high adaptability in the studied plants (Austin 1993; Araus *et al.* 2002). Beside, other previous findings by Cedola *et al.* (1994) had been indicated escape mechanisms in drought tolerant plants consisting of good winter growth (early vigor), high pre-anthesis leaf area index and leaf area duration, and high translocation of pre-anthesis assimilate to the ear.

2.1.2 Effects of Water Deficit on Different Growth and Developmental Stages

Water deficit may occur in any growth and developmental phase according to the environment in which the crop is grown. Therefore, understanding the plants growth and developmental phases and effect of water stresses on those stages becomes an essential step in the development of higher-yielding and more stable cultivars in drought stress conditions. It has been reported that the level of sensitivity to water deficit exists at all stages of plant development. In addition, the growth of small grain cereals may be divided into three major stages: planting to jointing, jointing to flowering, and flowering to physiological maturity. The most critical growth stage for wheat as far as water stress is concerned may be the jointing stage (Ottman *et al.* 2000; Garcı´a del Moral *et al.* 2003; Benmoussa and Achouch 2005). Water deficit during the shooting stage affect

spike number and particularly spike fertility (Weltzien and Srivastava 1981; Hadji christodoulou 1985; Garcı´a del Moral *et al.* 2003; Benmoussa and Achouch 2005).

2.1.3 Effect of Water Deficit on Germination and Seedling Stage

Seed germination involves the initiation of growth in a previously quiescent or dormant embryo. It is begun by moisture absorption, which is the uptake of water by the dry seed. The movement of water into the seed is due to diffusion and capillary action (Bradford 1990). Regarding to the importance of the roots function in uptake of the soil water, findings by Addaa *et al.* (2005) revealed that the length of seminal roots in durum wheat was affected with decreasing in the soil water content. The roots were significantly shorter under severe water stress conditions. Similar results have been observed in rice and barley seminal roots by Boonjung and Fukai (1996) and Sahnoune, *et al.* (2004), respectively. Contrasted results have been reported on adventitious root length in response to water deficit on cereals where limitation of moisture may promote longer roots in durum wheat (Ali Dib *et al.* 1994 and maize (Sharp *et al.* 2004). On the contrary, shorter roots were shown in barley (Thomas *et al.* 1995) and wheat (Mukharjee *et al.* 1991) under water deficit condition.

It has been reported that with increasing the osmotic stress, germination percentage and rate, coleoptile length, shoot length and shoot weight decreased significantly in bread wheat cultivars. Moreover, sever osmotic stress decreased root length and weight, whereas, thid parameter increased under mild osmotic stress (Ghodsi 2004). Coleoptile length is a useful seedling trait to improve crop establishment under current variable rainfall. Therefore, genotypes with a long coleoptile allow sowings at greater soil depth avoiding a 'false start' where rainfall is not sufficient to assure the establishment of the crop. It has also been shown that seed size, protein content and

initial root and aerial biomass are correlated in wheat. Several authors pointed out the positive effect of larger seed size on wheat germination and establishment (Hampton 1981; ICARDA 1987; Kalakanavar *et al.* 1989). In addition to these, Aparicio *et al.* (2000) reported that both seed and embryo size have proved to be key factors in determining the development and growth of durum wheat seedlings until the fourth leaf-stage. Finally, many researchers have reported the effect of stress duration on adventitious roots production (Grzesiak *et al.* 1991) others have demonstrated that water deficit severity in seedling stage is more important than the duration of the stress (Malik *et al.* 2002). Other authors have noticed that root growth is dependent on both stress severity and timing (Sahnoune *et al.* 2004).

2.1.4 Effect of Water Deficit on Morphological Aspects

Physiological and morphological characters that confer drought resistance can be classed according to their association to water absorption or water loss by the crop. They are related to an increase in water absorption, root growth, osmotic adjustment and related solutes and membrane stability. Among plant characteristics, tillering capability is considered as one of the main traits in response to different environmental conditions. De Vita *et al.* (2007) and also Slafer and Araus (2007) reported that the genetic gains of durum wheat have mainly been assigned to a balanced improvement in fertility because of higher assimilates to the growing tillers and spikes. It has been reported that low tillering ability in wheat genotypes showed a close association between the number of fertile tillers and grain yield. However, there was an inverse relationship between the number of fertile tillers and 1000-grain weight (Ozturk *et al.* 2006; Valério *et al.* 2009).

Environmental stresses particularly water deficit can cause changes in spike characteristics and its related reproductive traits, which are important organs in crop

production and also yield and yield components. Many researchers reported that water limitation at different growth and developmental stages affected the number of total and fertile spikelets and florets (Saini and Westgate 2000; Casati and Walbot 2004). The various effects of genotypes on tillering capacity have been previously reported by Acevedo *et al.* (2002), Ghodsi (2004), Izanloo *et al.* (2008), Valério *et al.* (2009) in bread wheat, Nazeri (2005) in triticale, De Vita (2007), Slafer and Araus (2007) in durum wheat and Samarah (2005) in barley. Various genotypes showed different number of total and fertile tillers under different environmental conditions. In addition, researchers reported that the ability of determinate tillering under optimum conditions is a very important characteristic in durum and bread wheat (Izanloo *et al.* 2008; Valério *et al.* 2009). Their results showed that by increasing tiller number under optimum conditions, mortality of the tillers increased under water stress conditions. Valério *et al.* (2009) reported that genotypes with low tillering ability have closer association with grain yield under water stress condition. It may cause maintenance of soil water for drought sussebtable stages such as grain filling. However, the results of Akram *et al.* (2008) revealed a negative correlation between tillers and spike length with grain yield at phenotypic and genotypic levels.

It has been reported that decreasing of the wheat plant height under terminal drought stress condition may be due to decrease in relative turgidity and dehydration of protoplasm, which is associated with a loss of turgor and reduced expansion of cell and cell division (Iqbal *et al.* 1999). Beside, several researchers have reported that plant height, ear length, number of spikelet, grain yield and straw weight decreased with water stress in both durum and bread wheat genotypes (Saleem 2003; Ghamarnia and Gowing 2005). The results of experiments on two spring durum wheat cultivars during different growth and developmental stages revealed that the severity of the drought stress and the type of damage depend on growth stage. The patterns of shoot apex

development in the studied cultivars were considerably different and played an important role in response to water stress. Consequently, a long duration of primordial initiation in Coleh durum wheat assisted this cultivar to have a better ability to resist water stress.

2.1.5 Effect of Water Deficit on Physiological Aspects

It has been shown that accessibility of water for plant growth is a key aspect determining plant distribution in natural ecosystems and is the most important limiting parameter in agricultural systems. Stress is the altered physiological condition by factors that tend to alter balance, while strain can be any chemical and physical change, which produced through a stress agent (Shao *et al.* 2008; Semenov *et al.* 2009).

2.1.5.1 Effect of Water Deficit on Growth Parameters

In order to determine what may influence a crop plant during the season, one often needs to know more than just the end yield or the final dry matter accumulation. Looking at the yield influencing factors and the plant development as net photosynthesis accumulation over time is one approach known as growth analysis, which can be made of individual plants or of plant communities. Measurements on individual plants may include: relative and absolute growth rates; unit leaf rate or net assimilation rate; leaf area ratio; specific leaf area and specific leaf weight in growth. Parameters used in plant community growth analysis include leaf area index, leaf area duration, crop growth rate of total biomass as well as net assimilation rate (Gardner *et al.* 2003).

Leaf area index (LAI) expresses the ratio of leaf surface area to the ground area occupied by the crop. This measurement is an attempt to optimize crop production strategies to maximize light interception by using leaf density and spatial arrangement

to cover ground area and promote rapid leaf expansion. Indeed, in a crop canopy, bare ground does not trap and convert light energy (Gardner *et al.* 2003). Previous reports by Shibles and Weber (1965) and Wilfong *et al.* (1967) showed a close relationship between the green LAI value and the amount of light being intercepted by the plant and dry matter production increases with LAI. Moreover, Brisson *et al.* (2001) suggested that water deficit reduces the leaf area index of crops and this constitutes a type of adaptation to water shortage, allowing the plant to reduce its areas of gas exchange and consequently, its evaporative surface, thus inducing a reduction in stress through an improved balance between soil water availability and evaporative demand. They also believed that efficiency of this mechanism varies as a function of species; it is particularly marked in wheat.

It has been reported that reduced leaf area and leaf area index (LAI) are a major mechanism for moderating water use and reducing injury under drought stress. Often, crop cultivars breed for water-limited environments by selection for yield under stress, have a constitutively reduced leaf area. Beside, reduced growth duration is associated with reduced leaf number (Mitchell *et al.* 1998; Blum 2004). According to Boyer (1970) and Bradford and Hsiao (1982), in most annual crops, a low leaf area index due to water deficit is associated with low specific leaf area values. Regarding to growth processes, it is known that leaf expansion is the first process to be affected by water deficit, well before stomatal closure, which causes a reduction in specific leaf area. The senescence processes bring about a remobilization of carbon reserves from senescing to functional leaves, which also tend to reduce the specific leaf area. In addition, the findings of Reynolds *et al.* (2001), Araus *et al.* (2002) on wheat and Nazeri (2005) on triticale exhibited a positive correlation between green leaf area index (GLAI) and radiation interception with grain yield for new varieties during grain filling. Besides, Giunta *et al.*

(2004) reported that in the period between beginning of stem elongation and heading on durum wheat, drought affected the maximum LA1 in the most stressed treatments.

Crop growth rate (CGR) is the gain in weight of a community of plants on a unit of land over a unit of time. Some plants are more efficient than others and the total crop growth weight can be compared to the economic crop growth weight to produce another useful quantity called the partitioning coefficient or index, an expression of the plant's efficiency in converting assimilate to economic yield. The reports of Richards *et al.* (2002) indicated that the early season crop growth rate under water deficit condition was very important for better establishment of the young plants and consequently to overcome the soil surface evaporation. In addition, Ghodsi (2004) and Nazeri (2005) have been suggested to decreasing of the LAI and CGR after anthesis due to growth stunt in the studied plants.

The relative growth rate (RGR) indicates the dry weight increase in plant matter over a time interval in relation to the initial weight. It is a commonly used parameter to measure the crop plant growth over time However, water deficit can be a main limiting factor for relative growth rate in semi-arid conditions, where strongly limits both growth and seedling survival through terminal growth (Moles and Westoby 2004). On the other hand, Ghodsi (2004) indicated that amongst growth parameters, the relative growth rate is an important calculable and dependable index, which was explained clearly differences of the grain yield under water deficit compared to well water irrigations. Besides, their findings indicated that CGR and RGR values were reduced under sever water deficit condition in comparison to optimum or low moisture deficit.

The net assimilation rate (NAR) is the net gain of assimilate by the plant per unit of leaf area and time. Age of the plant can distort this reading as this measurement assumes that the relationship between plant weight and leaf area is linear and, later

growth phases may have the growth rate of leaf area exceed that of dry matter or vice versa (Gardner *et al.* 2003). It has been revealed that a significant and positive correlation between RGR and NAR. Beside, with reduction of the RGR due to water deficit the NAR values decreased significantly (Poorter and Nagel 2000; Loveys *et al.* 2002).

In a greenhouse experiment, Simane *et al.* (1993) studied the responses of five durum wheat cultivars to moisture stress at different developmental phases and reported that total dry matter accumulation rate was different between drought resistant and susceptible cultivars. The relative growth rate and its components changed with age and moisture availability. They found that the drought resistant cultivars had a high RGR in favorable periods of the growing season and a low RGR during the moisture stress. In contrast, the drought susceptible cultivar showed an opposite trend. The LAR explained the differences in RGR best, whereas the relationship between NAR and RGR was not significant.

2.1.5.2 Effect of Water Deficit on Radiation Use Efficiency

The amount of radiation intercepted by the crop during the growing season depends on the amount of incident radiation and the ability of the crop to intercept it. The total amount of incident radiation to which the crop is exposed may be increased by changing the developmental response of the crop, so that the duration of the growing season may be longer. This has to take into account that anthesis should occur at the optimum time for a particular location. Such a trait has, however, already been optimized for most regions and crops (Evans 1993).

It has shown that radiation use efficiency might be affected by vapor pressure, water stress and nutrient availability (Jamieson *et al.* 1995; Ple´net *et al.* 2000;

Kemanian *et al.* 2004). According to findings of Acevedo *et al.* (2002), potential radiation use efficiency in strong light depends on several factors, which are adequate water, leaf arrangement, good leaf nutrition, an active Benson-Calvin cycle and dissipation of heat. Moreover, Giunta *et al.* (2004) indicated that radiation use efficiency was also lowered under drought stress. Muurinen and Peltonen-Sainio (2006) indicated that radiation use efficiency were similar for barley and wheat. Their result showed high biomass accumulation due to the high RUE values after heading under decreasing light levels.

2.1.5.3 Effects of Water Deficit on Remobilization of Stored Pre-Anthesis Assimilates

Grain filling is the final stage of growth in cereals where fertilized ovaries develop into caryopses. Its duration and rate determine the final grain weight, a key component of the total yield. In today's crop production systems with their high yield output, improvement in grain filling has become more challenging than ever (Saini and Westgate 2000; Zahedi and Jenner 2003).

According to Kobata *et al.* (1992) and Schnyder (1993), grain filling in cereals depends on carbohydrates from two resources: current assimilates transferred directly to the grain and assimilates redistributed from reserve pools in vegetative tissues either pre- or post-anthesis. Reserve pools provide the substrate needed to maintain transport and supply of assimilate to grains during the later grain-filling period, when the photosynthetic apparatus is senescing and the rate of dry matter accumulation of grains exceeds the rate of dry matter accumulation of the total crop.

Gebbing and Schnyder (1999) reported that under adequate moisture conditions, pre-anthesis assimilate reserves in the stems and sheaths of wheat and rice contribute 10–40% of the final grain weight. This may be partially linked to plant traits that

promote high yield potential, at least during the pre-flowering stages. Although some stem reserve mobilization may support grain filling under non-stress conditions, reserve mobilization noticeably induces by drought stress during grain filling (Yang *et al.* 2001; Plaut *et al.* 2004).

Any environmental stress that decreases plant water status and photosynthesis during grain filling induces stem storage conversion into soluble sugars and mobilization of sugars into the grains. The mobilization of sugars into the grain can take place in a dehydrated plant and it is apparently a dehydration-tolerance process in the whole plant. The capacity to store pre flowering stem reserves is most likely supported by a favorable plant water status. However, storage conversion into transportable carbohydrates and the transport them into the inflorescence take place as the whole plant dehydrates (Blum *et al.* 1983; Hossain *et al.* 1990).

Yang *et al.* (2000) showed that under some circumstances, drought might promote remobilization of nutrients from leaf and stem and increase the rate of grain filling. In addition, remobilization of reserves to the grain is critical for grain yield if the plants are subjected to water stress. On the other hand, stem reserve utilization has been found to be an effective yield-supporting mechanism under drought stress (Asseng and van Herwaarden, 2003; Plaut *et al.* 2004).

According to surveys conducted by Ehdaie *et al.* (2006), internodes including the peduncle, penultimate, and the lower internodes are components of the stem in wheat. In addition, they demonstrated substantial genotypic variation for stem length and stem weight in different internodes of the main stem. They also showed that dry matter accumulation and mobilization varied along the stem in well-watered and drought field conditions.

Mi *et al.* (2002) and Gong *et al.* (2005) reported that remobilization of assimilates stored in vegetative tissues to the grain in monocarp plants such as rice and wheat require the initiation of whole-plant senescence. Delayed in grain filling, which leads to poorly filled grains and unused carbohydrate in straw is a new problem increasingly recognized in rice and wheat production in recent years. Slow grain filling is usually associated with delayed whole plant senescence.

Water deficit coincide with anthesis accelerates development and the accumulation of soluble carbohydrates in the stem occurring between anthesis and the linear phase of grain growth is decreased (Nicholas and Turner 1993). The remobilization of pre-anthesis assimilates to the grain becomes important as photosynthesis is decreased by water stress (Kiniry 1993; Simane *et al.* 1993; Palta *et al.* 1994).

2.1.5.4 Effects of Water Deficit on Photosynthesis, Water and Temperature Balance in Plant

Drought can be a complex physico-chemical process, in which many biological macromolecules and small molecules such as nucleic acids, proteins, carbohydrates, lipids, hormones, ions and mineral elements are involved, (Romo *et al.* 2001; Pan *et al.* 2002).

In the field, plants are often exposed to environmental stresses, especially drought, high light, high and low temperature. As Blum (1996) noted, drought is a multidimensional stress affecting plants at various levels of their organization. At the whole plant and canopy levels, the plant response to drought is complex because it reflects the integration of stress effects and responses at all underlying levels of organization over space and time. At the whole plant level, the effect of stress is usually

perceived as a decrease in growth and photosynthesis (Cornic and Massacci 1996; Mwanamwenge *et al.* 1999).

Several lines of evidence indicate that a decrease in photosynthesis due to water deficit has been attributed to both stomatal and non-stomatal limitations (Ort *et al.* 1994; Shangguan *et al.* 1999). Stomatal closure is the first line of defense against dehydration, since it is much quicker than changes in roots growth, leaf area, and chloroplast ultra structure and pigment proteins. In many cases, the more drought tolerant species control their stomatal function to allow some carbon fixation at stress, thus improving water use efficiency. The relative role of stomatal limitation of photosynthesis depends on severity of water deficit. At mild stress, it is primal event, which is then followed by adequate changes of photosynthetic reactions. However, closing at long-term water deficit the non-stomatal limitation predominate (Cornic and Briantais 1991).

Significant decrease of the photosynthetic rate and stomatal conductance in wheat under water deficit condition was reported. The reduction was observed from 1 to 13 μmol m^{-2} s^{-1} in photosynthetic rate under water limitation (Fresneau *et al.* 2007; Olszewski *et al.* 2008). In addition, a significant genotypic difference by Labhilli *et al.* (1995), Subrahmanyam *et al.* (2006), Olszewski *et al.* (2008) and Izanloo *et al.* (2008) in photosynthetic rate and stomatal conductance within the wheat genotypes under well water and water stress conditions was observed. Findings by Izanloo *et al.* (2008) in wheat genotypes indicated that significantly negative correlations between stomatal conductance and leaf temperature under water deficit conditions prevailed, whilst there were no significant relationships between them under optimum irrigation.

A clear time dependency in stomatal responsiveness to air humidity and water status was also found and suggesting some of diurnal changes in stomatal function may

result from metabolic processes with a circadian rhythm. In addition, changes in cell carbon metabolism are also likely to occur early in the dehydration process (Franks *et al.* 1997; Chaves *et al.* 2002; Lawlor 2002). Water deficit close to anthesis accelerates growth and development (Simane *et al.* 1993), the accumulation of soluble carbohydrates in the stem occurring between anthesis and the linear phase of grain growth is decreased (Nicholas and Turner 1993).

With regard to the importance of the pre-anthesis dry matter contribution to grain, the remobilization of pre anthesis assimilates to the grain becomes important as photosynthesis is decreased by water deficit and total non-structural carbohydrates from wheat leaves and stems significantly contribute to grain growth (Kiniry 1993; Palta *et al.* 1994).

Findings of several workers (Bajji *et al.* 2001; Molnár *et al.* 2004; Dulai *et al.* 2006) on durum wheat genotypes revealed that with decreasing of relative water content in the leaves under water deficit condition, the water balance of plants disrupted. It also resulted in fast and considerable stomatal closure and finally decreased net photosynthetic fixation. Therefore, plants that are able to maintain high levels of relative water content under water deficit condition should be less affected by the stress and be able to maintain more normal growth and yield (Beltrano *et al.* 2006).

It is well known that the canopies with higher water content are indicative of genotypes with higher biomass resulting from larger rates of carbon fixation associated with greater stomata conductance and therefore, cooler canopies (Babar *et al.* 2006). Furthermore, Balota *et al.* (2007) indicated that canopy temperature depression (CTD) has been used to estimate crop yield and to rank genotypes for tolerance to drought. Additionally, the results by Siddique *et al.* (2000) showed that drought stress significantly decreased the relative water content, which had pronounced effects on

photosynthetic rate. They suggested that leaf and canopy temperature increased due to drought stress that might have occurred due to increased respiration and decreased transpiration resulting from stomatal.

2.1.5.5 Effects of Water Deficit on Osmotic Adjustment

Osmotic adjustment is considered to be an important component of drought tolerance mechanisms in plants. It is usually defined as a decrease in cell sap osmotic potential resulting from a net increase in intracellular solutes rather than from a loss of cell water. Plants under different environmental stresses accumulate low molecular weight organic solutes generically termed compatible solutes, which include amino acids and sugars. In addition to these organic substances, some inorganic solutes are also a significant fraction of the osmotic ally active solutes present in plant cells. Young expanded and growing leaves differed in terms of relative water content and osmotic adjustment (Blum 1996; Zhang 1999).

It has been well known that osmotic regulators include many important small molecules such as potassium, soluble sugars and proline. These small molecules are also important physiological indicators for evaluating the osmotic adjustment ability and drought resistance in wheat species and genotypes (Erdei *et al.* 2002; Rellegrineschi *et al.* 2002; Halford, and Paul 2003; Maathuis *et al.* 2003; Shinozaki and Dennis 2003; Yordanov *et al.* 2003; Capell *et al.* 2004; Costa *et al.* 2004; Dhanda *et al.* 2004; Wenzl *et al.* 2004; Shao *et al.* 2005).

Several workers have been suggested that the capacity of osmotic adjustment is greater in growing than in expanded leaves and sugars are the main solutes that contribute in osmotic adjustment particularly in growing leaves followed by proline and quaternary ammonium compounds. In addition, the degree of osmotic adjustment could

be affected by the rate of stress development and most particularly by organ type and age (Kameli and Lösel 1995; Shangguan 1999; Bajji *et al.* 2001).

In wheat, osmotic adjustment was suggested to be an important factor explaining differences in genotype yield or yield stability (Teulat 1997). Proline repeatedly has been shown to increase under water stress and is potentially important contributor to osmotic adjustment (Ali Dib *et al.* 1994; Rascio *et al.* 1994; Mattioni *et al.* 1997). Although, it has been suggested that proline is not directly involved in the drought tolerance and is not essential for improved resistance. Nevertheless, where proline increase does occur it improves resistance (Errabll *et al.* 2006). Bayoumi *et al.* (2008) reported that in wheat, relationship between grain yield and proline accumulation was correlated positively under water deficit condition. Therefore, the sharp increased in proline content might be an adaptation mechanism to overcome the stress condition and it could supply energy for growth and survival and thereby help the plant to tolerate stress (Sankar *et al.* 2007).

Osmotic adjustment helps plants to perform better in drought in terms of growth and productivity through maintaining turgor and water supply to the plant, which thereby maintains a comparatively higher photosynthetic rate and growth (Ludlow and Muchow 1990; Blum *et al.* 1999; Subbarao *et al.* 2000). Occurrence of osmotic adjustment at reproductive stages of sensitive crops has been reported to play a constructive role against floral abortion, which results in maintaining grain number under water deficit (Leport *et al.* 1999; Moinuddin and Khanna-Chopra 2004). Additionally, it has also been claimed that osmotic adjustment facilitates a better translocation of pre-anthesis carbohydrate reserves to the grain during the grain-filling period (Subbarao *et al.* 2000). Accumulated proline plays as a compatible solute regulating and reducing water loss from the cell under water deficit condition. In addition to this, their findings showed that high relative water content and proline were

identified as beneficial drought tolerance indicators and may be used as selection criteria in wheat breeding programs (Bayoumi *et al.* 2008).

2.1.6 Effects of Water Deficit on Yield and Yield Components

The dramatic increase in world food production over the past half century has been from increased crop yields. It is generally agreed that future increase in world food production will become even more dependent on increased yield as the amount of cultivated area in the world continues to decrease. Increased yields have been accompanied by increased water productivity through a variety of the plant ecophysiological parameters (Keller and Keller 2003).

It has been clearly documented that there is a need to develop drought resistant cultivars with higher grain yield than current cultivars for planting under drought stress conditions. In addition, it was reported that selection for high yield under stress free conditions has, to a certain extent, indirectly increased final yield production under water-limiting conditions (Pantuwan *et al.* 2002; Cattivelli *et al.* 2008).

Grain yield in wheat can be analyzed in terms of three yield components (number of spikes per square meter, number of grains per spike, and grain weight) that appear sequentially with later-developing components under control of earlier developing ones (Garcı´a del Moral *et al.* 1991). The results of growth chamber experiments by Izanloo *et al.* (2008) revealed that grain number per spike and the percentage of aborted tillers were the major yield components that affected wheat grain yield under water stress.

Moisture regime affected the number of spikes per square meter and grains per spike, and consequently grain yield, and explained 60% of the total variation for these characters (Sharif-Alhosainy 1998; Khazaei 2002; Ghodsi 2004). Other studies have

shown that the number of grain spike^{-1} has a predominant importance over grain weight in defining yield in high latitudes (Peltonen-Sainio *et al.* 2007) whereas, grain weight is well known as a major yield component and it determine final yield in certain Mediterranean environments (García del Moral *et al.* 2003).

Several researchers reported negative effects of water deficit during anthesis to grain filling on yield and yield components of the cereals crops. Decreasing of grain filling period has been caused a reduction in grain weight and 1000-grain weight in durum and bread wheat genotypes (Sharif-Alhosainy 1998; García Del Moral *et al.* 2003; Saleem 2003; Kirigwi *et al.* 2004). Moreover, other researchers (Donalson 1996; Nazeri 2005) reported that water deficit after anthesis decreased grain filling period, grain weight and crop production.

Variations in grain yield between moisture regimes were predominantly associated with variations in spikes per square meter and grains per spike. This result agrees with previous reports under water-limited conditions (Garcı´a del Moral *et al.* 1991; Simane *et al.* 1993). Giunta *et al.* (1993) reported that severe water deficit at anthesis impose a negative effects on wheat yield, reducing the number of spikes and spikelet and therefore causing a decrease in plant fertility. Besides, it may lead to a loss in yield by reducing spike and spikelet number and the fertility of surviving spikelets. Zhong-hu and Rajaram (1994) found that spikes per square meter and grains per spike were the yield components most sensitive to drought while grain weight remains relatively stable due to high remobilization of stored pre anthesis assimilates.

Garcı´a del Moral *et al.* (2003) reported that drought in rainfed conditions caused reductions in grain yield estimated at 50 and 43% under cooler and warmer conditions, respectively. Spikes per square meter was the most sensitive yield component to drought stress and was reduced by 37 and 34% under rainfed conditions

at both the cool and warm temperature regimes, respectively. Two durum varieties (Altar and Jabato) produced satisfactorily yields because they had a high number of spikes per square meter and grains per spike. In contrast, spikes per square meter had a negative direct effect on grains per spike and grain weight in the irrigated and rainfed sites under the warmer conditions.

It has been reported that number of spikelets per spike and number of grains per spike in bread and durum wheat decreased significantly under water stress. Terminal drought stress significantly reduced the grain weight in all durum wheat genotypes. The decrease in grain weight may be due to disturbed nutrient uptake efficiency and photosynthetic translocation within the plant that produced shriveled grains due to hastened maturity (Iqbal *et al.* 1999; Saleem 2003).

2.1.7 Effects of Water Deficit on Biomass and Harvest Index

Farmers are concerned more with economic yield than with total biological yield. the proportion of total biomass production, which is invested into harvested parts of the plant, is termed harvest index. Harvest index has been reached near 50% for important crops, including wheat, rice, maize, barley and oat (Sharma-Natu and Ghildiyal 2005). Previous findings by Perry and D'Antuono (1989) indicated that achievements in breeding for wheat grain yield have been attributed to increases in harvest index, with only slight increases in biomass. However, in the durum wheat derived from International Maize and Wheat Improvement Center (CIMMYT), biomass under optimal growth conditions increased 30% from 1969 to 1985, and improvements in grain yield potential in modern CIMMYT durum wheat have resulted from higher biomass.

Clarke *et al.* (1991) and Ashraf (1998) showed that plant produce their maximum biomass under adequate water supply, whereas moisture stress causes a marked decrease in plant biomass production. Hence, in addition to other factors, dry matter production can be used as a selection criterion for drought tolerance. In addition, Saleem (2003) reported that terminal drought stress caused a significant reduction in plant dry mass of all genotypes of both durum and bread wheat. Durum wheat genotypes showed comparatively less reduction in biomass production than bread wheat genotypes, and reduction in dry matter accumulation was in all genotypes.

2.1.8 Water Use Efficiency

Water use efficiency (WUE) is a wide concept that can be explained through various ways. For farmers and soil managers, water use efficiency is the yield of harvested crop product achieved from the water available to the crop due to rainfall, irrigation and the contribution of soil water storage. Water use efficiency varies substantially between crops, for example, to produce 1 kg of grain on average requires 900 liters for wheat (*Triticum spp*), 1400 liters for maize (Zea mays) and 1900 liters for rice (Oriza sativa). In addition, there are great prospects for increasing the water use efficiency of specific genotypes within each crop. Therefore, improving water use efficiency in agriculture will require an increase in crop water productivity and a reduction in water losses from the plant-rooting zone, a critical zone where adequate storage of moisture and nutrients are required for optimizing crop production (Pimentel *et al.* 1997).

With regard to importance of increasing water use efficiency in crop production, agriculture must aim to improve all aspects of water management as well as developing crop cultivars with a higher efficiency of water utilization. Hence, plants with elevated water use efficiency have a higher stomatal conductance, implying a positive balance

between carbon and water exchange. In addition to this, an increase in water use efficiency with high stomatal density might also indicate a high acclimation capacity to a gradually increasing water deficit, and suggest an evolutionary adaptation to environmental stresses (Xu and Zhou 2008).

Water use efficiency decreased with increasing evapotranspiration, (Aggarwal *et al.*, 1984), whereas it did not change with seasonal evapotranspiration (Musick *et al.*, 1994). On the other hand, numerous studies have been shown that early response to water deficit is a reduction in leaf area and plant growth, which allows plants to reduce their transpiration rate, thus increasing water use efficiency and promoting interspecies competition capacity under drought (Aguirrezabal *et al.* 2006; Monclus *et al.* 2006; Xu *et al.* 2007; Xu and Zhou 2008). The increase in yield potential achieved by plant breeding has been well documented for numerous crops, but fewer studies have concentrated on the genetic gain in water use efficiency (Cattivelli *et al.* 2008). Although inter- and intra-genotypic variation in water use efficiency has been recognized since the beginning of the 20th Century, little progress has been made in understanding this variation until 1990s (Thumma *et al.* 1998; Tsialtas *et al.* 2002).

In has been concluded that improved water use efficiency for grain in modern cultivars was associated with rapid decline in groundwater (Siddique *et al.* 1990). However, the positive correlation between grain yield and water use efficiency for wheat cultivars indicated that using a higher yielding cultivar has the potential to improve water use efficiency and thereby to save water (Zhang *et al.* 2009). In addition, several findings have been indicated that timing and the amount of irrigation greatly affects yield and crops water use efficiency (Al-Kaisi *et al.* 1997; Zhang *et al.* 2003, 2005).

According to results of the greenhouse experiments by Blum (2005), water use efficiency was similar in high-yielding semi-dwarf cultivar and landrace of durum

wheat cultivars in the control condition while, it increased under water deficit condition. Furthermore, high-yielding semi-dwarf cultivar compared to the landrace indicated higher values for water use efficiency under water deficit conditions due to the relative differences in their water use and biomass production.

A number of previous results (Farquhar and Sharkey 1982; Matthews and Boyer 1984; Bunce 1988; Vassey and Sharkey 1989) have been shown that both stomatal and non-stomatal parameters are thought to contribute to drought effects on water use efficiency. In addition, another plausible mechanism for increased WUE is improved mesophyll capacity for photosynthesis, which allows photosynthesis rate to increase and leaves rate of transpiration unaffected. However, recent findings (Zhang *et al.* 2009) were indicated no significant relationships between water use efficiency and physiological traits such as ash content, chlorophyll content, or relative water content among the new wheat cultivars. Although, similar with previous results, a significant correlation was found between stomatal conductance and water use efficiency or grain yield. Moreover, the relationships between WUE, date of anthesis and harvest index were appeared significant and earlier flowering cultivars tended to have higher grain yield.

2.1.9 Genetic Control of Drought Tolerance

However, it is interesting but not surprising that genetic increase in wheat yields in dry areas has not been as great as in more favorable environments or where irrigation is available. A likely reason for this is that those dry environments are characterized by unpredictable and highly variable seasonal rainfall and hence highly variable yields. Since yield has a complex trait and is strongly influenced by the environment, sever losses can be caused by drought, a stress common in most arid and semi arid areas. Accordingly, drought tolerance is one of the main components of yield stability and its

improvement is a major challenge to geneticists and breeders. Therefore, sufficient genetic information regarding the yield traits of wheat under drought is essential and important to get progress in plant breeding program. Moreover, understanding of the genetic control of these economic traits through quantitative traits locus analysis allows the identification of discrete chromosome segments controlling complex traits (Frova *et al.* 1999; Manal 2009).

2.1.10 Drought Tolerance Indices

Drought stress greatly affects productivity and growth of plants and plays a principal role in their geographical distribution. Water deficit induces a set of physiological and biochemical responses in plants and is one of the most complex stress conditions. Drought stress depends not only on the severity and duration of the stress event, but also on the plant developmental stage and morphology (Rizhsky *et al.* 2002; Bartels and Sunkar 2005). Moreover, in arid and semiarid regions of the Mediterranean, wheat crops usually envisage drought during the grain-filling period and drought stress at this period decreases grain yield, considerably (Ehdaie and Waines 1996).

Various quantitative indices have been proposed for selection of genotypes based on their yield performance in drought stress and non-stress environments. In addition, they reported that water stress indices, which provide a measure of drought, based on loss of yield under drought conditions compared to normal conditions have used for screening drought-tolerant genotypes (Fernandez 1992; Kristin *et al.* 1997; Golestani and Assad 1998; Mitra 2001; Farshadfar and Sutka 2003; Ghodsi 2004; Nazeri 2005).

In order to evaluate the wheat genotypes to drought tolerance under water deficit conditions, several workers suggested using drought indices, particularly stress

susceptibility index (SSI), tolerance (TOL), mean productivity (MP), stress tolerance index, (STI), geometric mean productivity (GMP), relative performance (PR) and stress intensity (SI) (Fischer and Maurer 1978; Rosielle and Hamblin 1981; Clarke *et al.* 1992; , Ghodsi 2004; Nouri-Ganbalani *et al.* 2006; Mohammadi *et al.* 2006). According to Aghaee *et al.* (2006) the durum wheat lines with highest STI, showed the minimum fluctuation on yield under both the control and drought conditions. The lines with highest STI showed highest membrane stability and yield level compared to the other lines.

CHAPTER 3

OSMOTIC STRESS-INDUCED CHANGES ON GERMINATION AND SEEDLING GROWTH OF PROMISING DURUM WHEAT GENOTYPES

3.1 INTRODUCTION

Drought is a major abiotic stress in many agricultural lands throughout the world. Large parts of agricultural regions are subjected to mild or severe abiotic stresses. In these areas, water deficit decreases crop productivity more than any other environmental stress. One of the important challenges facing crop physiologists and agronomists is understanding and overcoming the major abiotic stresses in agriculture, which reduces crop productivity and yield. Drought stress particularly predominant in arid and semi-arid regions and consecoently, it decrease crop yield (Casati and Walbot 2004; Dai and Li 2004; Canadian Food Inspection Agency 2006).

Drought stress is affecting the different growth and development stages in a plant and many investigations. Seed germination is considered to be one of the most critical growth stages under water stress conditions, as it is a requirement for the success of the stand establishment of crop plants. Several studies reported that increasing osmotic stress in bread wheat varieties decreases the germination percentage and rate, coleoptiles length, root and shoot length, dry weight of root and shoot significantly (Jaradat and Dawayri 1981; Ashraf *et al.* 1992; Dhanda *et al.* 2004; Ghodsi 2004; Rauf *et al.* 2007; Yagmur and Kaydan 2008).

Varietals differences in drought tolerance have been reported previously in wheat and several other crops (Johnson 1981; Steiner *et al.* 1990). Radhouane (2007) showed that genotypes with longer root under water stress conditions are able to access deeper water in the soil. He suggested that increase in root length was an adaptive response drought stress. Several workers have reported the relationships between water stress with drought tolerance using drought indices in different cereals such as durum

wheat (Fernandez 1992; Arzani 2002; Golabadi *et al.* 2006), bread wheat (Ghodsi 2004) and triticale (Nazeri 2005).

Ashraf *et al.* (1992) have suggested that development of drought tolerant varieties can be a useful approach to increase crop production and yield under water stress conditions. With regard to the importance of seed germination for the successful stand establishment of the crop plants, the following objectives were considered in this study.

1. To determine the osmotic stress and genotype affects on different traits of the promising durum wheat genotypes at the germination and seedling stage.
2. Identification of the drought tolerant and susceptible genotypes under different levels of the osmotic stress conditions using drought stress indices for using in the field experiments.
3. To determine the germination sensitivity thresholds to water stress in the promising durum wheat genotypes.

3.2 MATERIALS AND METHODS

Laboratory studies were conducted at the Institute of Biological Sciences, University of Malaya. It was laid out in factorial experiments based on a completely randomized design (CRD) with three replications and two factors. The first factor was osmotic stress at four levels, i.e. 0.0, 0.3, 0.6 and 0.9 (-MPa) (Afzal *et al.* 2004; (Rehman *et al.* 2004; Nazeri 2005). The second factor was 20 promising spring durum wheat genotypes with same ages. The seeds of the various durum wheat genotypes as shown in Appendix 3 were obtained from the elite durum yield trial (2006 - 2007) carried out at the Seed and Plant Improvement Institute, Iran.

3.2.1 Preparation of Solutions for Different Osmotic Potentials

Osmotic stresses (0.3, 0.6, and 0.9 -MPa) were produced using different concentrations of polyethylene glycol 6000 (PEG) at 20°C according to the method of Michel and Kaufmann (1973) as follows:

$$WP = 1\ (1.18e^{-2})\ C - (1.18e^{-4})\ C^2 + (2.67e^{-4})\ CT + (8.39e^{-7})\ C^2T$$

In this formula, WP is the osmotic potential of the solutions (PEG-6000) as the moisture stress (bar), C is the concentration of the PEG (g L^{-1} distilled water) and T is the temperature in centigrade. Consequently the amount of PEG used for each concentration (0.3, 0.6, and 0.9 -MPa) were 143.18, 213.64 and 267.98 g L^{-1} distilled water, respectively.

3.2.2 Preparation of Seeds for Germination

The seeds were germinated using the filter paper method, on 9 cm diameter Petri dishes on the top of the filter papers. Twenty healthy and uniform sized seeds of each genotype were selected and surface soaked with a plant fungicide (Carboxin Tiram) and then sterilized with 5% sodium hypochlorite solution for three seconds. The seeds were washed with distilled water and germinated in covered sterilized Petri dishes containing germination paper moistened with 8 mL of the different water potential. The Petri dishes were kept in an incubator for 8 days at 20 ± 0.5 °C (Rehman *et al.* 1996; Ghodsi 2004).

3.2.3 Determination of Germination Percentage and Rate

Data were recorded daily. For germination purposes, only those seeds that will approximately 2 mm of root length were considered as germinated seeds (Sapra *et al.* 1999; Afzal *et al.* 2004). The number of seeds germinated was counted daily 8 days and the germination percentage was estimated. Mean germination time (MGT) was calculated to assess the germination rate (GR) according to Ellis and Roberts (1980) and Sapra *et al.* (1999) as follows:

$$MGT = \sum (f\,x) / f$$

$$GR = 1/MGT$$

where, f is the number of newly germinated seeds on each day and x is the day of counting.

3.2.4 Measurement of the Seedling Traits

To measure the coleoptile length, 12 h of light was given after the fourth day, to the seedlings in the incubator. At the end of the eighth day, 5 seedlings were randomly

selected and the coleoptiles root, shoot and also seedling length were measured. Additionally, root, shoot and seedling dry weight were measured after drying samples at 76 °C for 48 h in a Growth chamber.

3.2.5 Determination of Germination Stress Index (GSI)

Based on Bouslama and Schapaugh (1984), the germination stress index (GSI) was calculated as follows:

$$GSI = (PISS / PICS) * 100$$

In this formula, PISS is the promptness index of seeds under stress condition while the PICS is the promptness index of those seeds under control contiotion (unstress condition). The promptness index (PI) was calculated as:

$$PI = nd2\ (1.00) + nd4\ (0.80) + nd6\ (0.60) + nd8\ (0.40)$$

where, nd2, nd4, nd6 and nd8 are germination percentages on the second, fourth, sixth and eighth day, consecutively.

3.2.6 Determination Germination Stress Tolerance Index (GSTI)

Stress tolerance index (STI) was calculated during the germination stage using the Fernandez (1992) formula as follows:

$$GSTI = (Yp * Ys) / (\ddot{Y}^2 p)$$

In this formula, yield potential (Yp) and yield stress (Ys) shows the value of each genotype under normal and the stress conditions. $\dot{Y}^2 p$ is the mean square for all genotypes under normal and stress conditions.

3.2.7 Data analyses

The data were collected and subjected to analysis of variance. It was statistically performed according to factorial experiments using MSTAT-C software packages. Data expressed as a percentage can vary only from 0-100%, and are thus not normally distributed. Two common conversions of such data are illustrated below. Square-root Transformation simply reduces the 0-100 scale to 0-10, and may lead to normalization of the Data. Arsine or Angular conversions employ the spreadsheet format ASIN (arc sine) square root of percentage. Therefore, for all the investigated parameters, analysis of variance was statistically performed according to factorial experiments. Data analysed using MSTAT-C and arcsine data transformation was performed for variance uniformity in percentage of germination data. Then all treatments were compared using Duncan's Multiple Range Test ($p < 0.05$ and 0.01) with the values of the least significant digits (LSD). Pearson simple correlation coefficient amongst different germination traits were also calculated using SPSS software packages (Ghodsi 2004; Moosavi *et al.* 2009)

3. 3 RESULTS AND DISCUSSION

3.3.1 Germination Percentage and Rate

The results (Appendix 5) revealed that the germination percentage and rate were significantly affected by osmotic stress and genotype treatments ($p < 0.01$). In addition, the interaction effects of osmotic stress and genotype was highly significant for the germination percentage, whereas it was no significant for the germination rate. There was a significant decrease in germination percentage of durum wheat genotypes with increasing osmotic stress. The highest value was observed was 93.5% in S1 (distilled water control) and the lowest (42%) in the S4 (-0.9 MPa) treatment (Fig. 3.1).

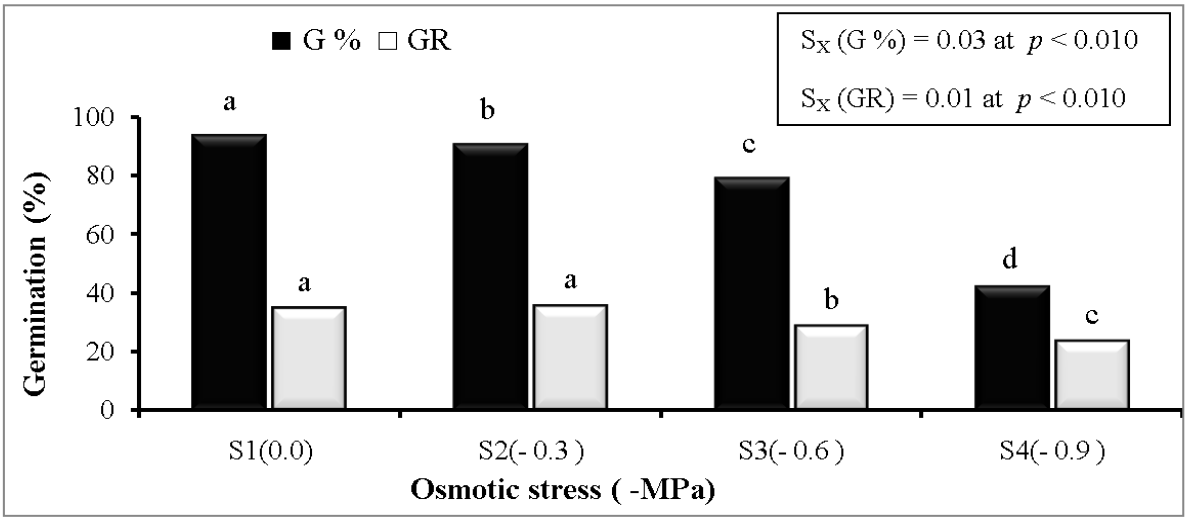

Fig. 3.1. The effect of osmotic stresses on germination percentage (G%) and germination rate (GR) of durum wheat genotypes

The overall results of the germination rate were similar to that shown in the germination percentage experiments (Fig. 3.1). Similar reductions in the germination percentage and rate affected by increasing osmotic stress have been reported by other workers in bread wheat (Ghodsi 2004; Rauf *et al.* 2007), durum wheat (Jaradat and Dawayri 1981) and in triticale (Nazeri 2005; Kaydan and Yamur 2008). The probable explanation for these observations is that there was a decrease in water uptake ability by

the seeds during germination and the seedling stage and this subsequently decreased the germination percentage and rate in the water stressed seeds.

Table 3.1 Genotypic effects of the different durum wheat genotypes on germination percentage (G %) and germination rate (GR)

Genotype	G%	GR%
G1	84.13 ^{a}	27 ^{bcd}
G2	76.20 ^{ab}	30 ^{abcd}
G3	73.33 ^{ab}	29 ^{abcd}
G4	84.17 ^{a}	35 ^{a}
G5	73.33 ^{abc}	29 ^{abcd}
G6	81.67 ^{a}	34 ^{ab}
G7	71.25 ^{bc}	29 ^{abcd}
G8	73.75 ^{abc}	29 ^{abcd}
G9	78.75 ^{a}	30 ^{abcd}
G10	80.42 ^{a}	34 ^{abc}
G11	79.58 ^{ab}	33 ^{abc}
G12	81.67 ^{a}	26 ^{cd}
G13	76.67 ^{ab}	31 ^{abcd}
G14	72.92 ^{abc}	28 ^{abcd}
G15	73.75 ^{ab}	31 ^{abcd}
G16	69.58 ^{abc}	28^{abcd}
G17	62.92 ^{c}	28^{d}
G18	82.92 ^{a}	32 ^{abcd}
G19	71.25 ^{abc}	28^{abcd}
G20	72.92 ^{ab}	29 ^{abcd}

Column sharing the same letters indicates no significant differences (S_X G% = 0.06 and S_X GR= 0.02 at $p < 0.010$)

As shown in Table 3.1, the various genotypes showed different responses in germination percentage and rate. Genotype four (G4) exhibited the highest (84.17%) whilst G17 showed the lowest germination percentage (62.92%) amongst all the genotypes. In addition, the highest and lowest values for germination rate were also obtained from G4 (35%) and G17 (25%) genotypes, respectively. These results were concurred with the reports of Dhanda *et al.* (2004), Nazeri (2005) and Rauf *et al.* (2007). They suggested that genetic differences between wheat cultivars cause significant differences in the germination percentage and rate under osmotic stress conditions.

Regarding to highly significant of the analysis of variance for interaction effects of osmotic stress and genotype in the germination percentage, the data summarize as in Table 3.2. It shows that with increasing osmotic stress from S1 to S4, germination percentage significantly decreased in most of genotypes. However, there were no significant differences between S1 (destilled water) and S2 (low osmotic stress). Amongst studied genotypes under different osmotic stress condition, G4 and G17 indicated the highest (100 %) and lowest (6%) germination percentage under S1 (distilled water) and S4 (-0.9 MPa) osmotic stresses, respectively. On the other hand, the highest and lowest germination percentages under sever (S4) osmotic stress condition were belonged to G1 and G17. Whereas, G1 and G3 indicated the maximum and minimum values under moderate (S3) stress compared to other genotypes.

Table 3.2 Interaction effect of osmotic stress × genotype on germination percentage of durum wheat genotypes

Osmotic stress	Genotypes									
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
S1	72.33$^{b\text{-}n}$	95.0^{abcd}	98.33^{ab}	100.0^{a}	93.33^{abcd}	95.00^{abcd}	95.00$^{a\text{-}e}$	95.00^{abcd}	99.0^{a}	86.67$^{a\text{-}g}$
S2	95.33^{abcd}	88.3^{abcde}	98.33^{ae}	91.67$^{a\text{-}f}$	91.67$^{a\text{-}e}$	85.00$^{a\text{-}h}$	85.00$^{a\text{-}j}$	88.33$^{a\text{-}h}$	90.0$^{a\text{-}i}$	91.67$^{a\text{-}g}$
S3	89.33$^{a\text{-}i}$	81.6$^{b\text{-}l}$	61.67$^{e\text{-}p}$	85.00$^{a\text{-}j}$	73.33$^{c\text{-}n}$	73.33$^{a\text{-}i}$	73.33$^{k\text{-}q}$	75.00$^{c\text{-}n}$	70.0$^{d\text{-}o}$	83.33$^{a\text{-}h}$
S4	79.00^{bn}	40.0$^{k\text{-}q}$	35.00$^{m\text{-}q}$	60.00$^{e\text{-}p}$	35.00$^{m\text{-}q}$	31.67$^{i\text{-}q}$	31.67$^{o\text{-}q}$	36.67$^{m\text{-}q}$	55.0$^{g\text{-}p}$	60.00$^{b\text{-}m}$

Tbable 3.2 (cont.)

Osmotic stress	Genotypes									
	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20
S1	93.3^{abcd}	96.67^{abcd}	91.67$^{a\text{-}e}$	90.00$^{a\text{-}g}$	96.67^{abc}	93.33$^{a\text{-}g}$	90.00$^{a\text{-}f}$	98.33^{a}	93.33^{abcd}	93.33^{abcd}
S2	90.0$^{a\text{-}h}$	91.67$^{a\text{-}e}$	90.00$^{a\text{-}f}$	81.67$^{b\text{-}k}$	95.00$^{a\text{-}d}$	88.33$^{a\text{-}g}$	85.00$^{a\text{-}j}$	95.00$^{a\text{-}e}$	83.33$^{a\text{-}k}$	93.33$^{a\text{-}e}$
S3	80.0$^{b\text{-}m}$	78.33$^{b\text{-}m}$	76.67$^{b\text{-}n}$	85.00$^{a\text{-}j}$	86.67$^{a\text{-}j}$	78.33$^{b\text{-}n}$	70.00$^{l\text{-}q}$	78.33$^{b\text{-}l}$	85.00$^{b\text{-}n}$	85.00$^{a\text{-}i}$
S4	55.0$^{h\text{-}q}$	60.00$^{e\text{-}p}$	48.33$^{j\text{-}q}$	35.00$^{m\text{-}q}$	16.67$^{p\text{-}q}$	18.33$^{o\text{-}p}$	6.67^{q}	60.00$^{f\text{-}p}$	20.00$^{n\text{-}q}$	20.00$^{p\text{-}q}$

Row sharing the same letters indicates non-significant differences (S_X = 0.13 at $p < 0.010$)

3.3.2 Coleoptiles, Root and Shoot Length and Root to Shoot Length Ratio

The analysis of variance (Appendix 5) indicated that the effect of osmotic stress on coleoptiles, root and shoot lengths and also root to shoot length ratio were highly significant (p <0.01). Moreover, the genotype effect for coleoptiles and root length was significant (p <0.05). In addition to this, interaction effect of the osmotic stress × genotype was also significant at p <0.05 for coleoptiles.

As can be seen in Fig. 3.2 the largest coleoptiles, root and shoot lengths were observed in the S1 treatment whilst the shortest growth were observed in the S4 osmotic stress level. However the influence of osmotic stress on decreasing shoot length was more than its effect on decreasing coleoptiles and root lengths. It was observed that coleoptile, root and shoot lengths decreased with increasing osmotic stress, whereas root to shoot length ratio increased (Fig. 3.3). These findings agree with the results reported by Jaradat and Dawayri (1981) on durum wheat and Dhanda et al. (2004) and Addaa *et al.* (2005) working on bread wheat. Nazeri (2005) and Yamur and Kaydan (2008) studying triticale and Okçu *et al.* (2005) working on rice reported similar results as well.

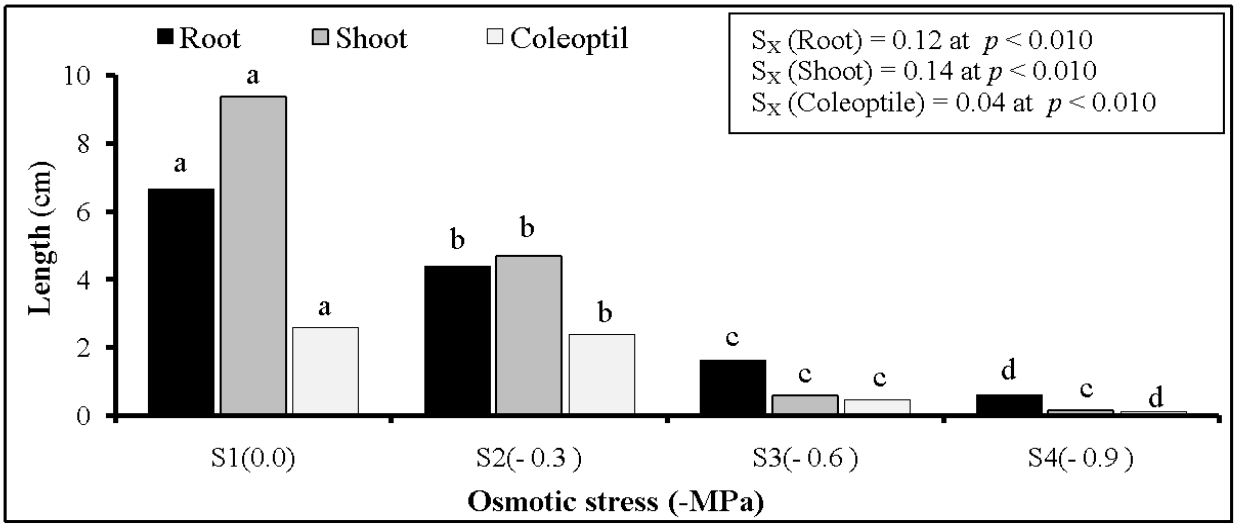

Fig. 3.2. The effect of osmotic stress on coleoptiles, root and shoot lengths of durum wheat genotypes

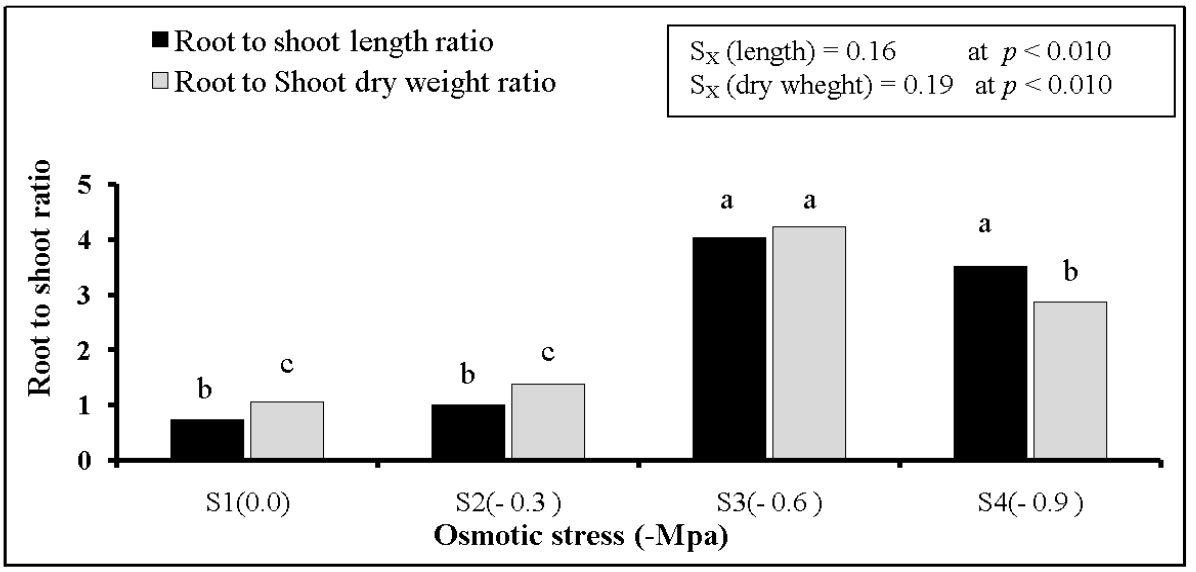

Fig. 3.3. The effect of osmotic stress on root to shoot lengths and dry weight ratio of durum wheat genotypes

According to Miralles *et al.* (2000), the reduction in growth affected by osmotic stress causing a decrease in cell size and also the rate of cell division in plant roots and shoots. Dhanda *et al.* (2004) suggested that selection of the genotypes according to the root length and root to shoot length ratio under osmotic stress may be a useful method in predicting the drought tolerance of genotypes. The results showed that the highest and lowest root lengths were obtained in the G7 and G8 genotypes. In addition, the maximum values for the coleoptiles length was observed in G14, whilst the minimum values was observed in G15 genotypes (Table 3.3). Dhanda *et al.* (2004) showed that under drought condition, genotypes with strong root growth are particularly important to avoid drought.

The comparison of the mean for the interaction effect of the osmotic stress and genotype indicated that with increasing osmotic stress, coleoptiles length decreased in all the genotypes (Table 3.4). On the other hand, there were no significant differences in coleoptiles length between S1 with S2 and also between S3 with S4 treatments. In general, the results showed that the largest coleoptiles lengths were belonged to the G20

genotype under the control condition whilst the lowest value was observed for the G17 under the S4 treatment (Table 3.4).

The interaction effect of osmotic stress × genotype indicated that the highest and lowest root to shoot length ratio were observed in S3G17 and S1G18 treatments, respectively (Table 3.5). The results also exhibited that the negative effect of the osmotic stress on the root growth was less than the shoots. Thus, the lower reduction of the root length compared to shoot length under osmotic stress conditions has increased root to shoot length ratio. These results corresponded with the results of Dhanda *et al.* (2004) and Ghodsi (2004).

Table 3.3 Response of the coleoptiles, root length and root dry weight to genotypic effects in durum wheat genotypes

Traits	Genotypes									
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
Coleoptiles (cm)	1.51 ^{abc}	1.46 ^{abc}	1.27 ^{abc}	1.35 ^{abc}	1.55 ^{ab}	1.56^{ab}	1.34^{abc}	1.25 ^{abc}	1.28 ^{abc}	1.46 ^{abc}
root length (cm)	3.31^{abcd}	3.14^{bcd}	3.36 ^{abcd}	3.01^{bcd}	3.08^{bcd}	3.39^{abcd}	4.08 ^{a}	2.69^{d}	3.15^{bcd}	3.29^{abcd}
Root dry weight (mg)	4.75 ^{abcd}	3.68^{d}	4.05^{cd}	5.90 ^{a}	4.43 ^{abcd}	5.57 ^{ab}	4.26^{bcd}	4.73^{abcd}	4.48^{abcd}	5.8 ^{a}

Table 3.3 (cont.)

Traits	Genotypes									
	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20
Coleoptiles (cm)	1.46 ^{abc}	1.21 ^{c}	1.28 ^{abc}	1.57 ^{a}	1.18 ^{c}	1.35 ^{abc}	1.24^{bc}	1.47 ^{abc}	1.45 ^{abc}	1.51 ^{abc}
root length (cm)	3.63 ^{abc}	3.50 ^{abcd}	2.93^{cd}	3.14^{bcd}	2.99^{cd}	4.05 ^{a}	3.00^{cd}	3.35 ^{abcd}	3.90 ^{ab}	3.40 ^{abcd}
Root dry weight (mg)	5.08^{abc}	4.21^{abc}	4.72 ^{abcd}	5.24^{abc}	4.86^{abcd}	4.36^{bcd}	4.39^{bcd}	4.51^{abcd}	4.92^{abcd}	4.9^{abcd}

Row sharing the same letters indicates non-significant differences (S_X coleoptile = 0.09, S_X root= 0.26, S_X dry weight=0.44 at $p < 0.050$)

Table 3.4 Interaction effect of osmotic stress × genotype on coleoptiles length of durum wheat genotypes

Osmotic stress	Genotypes									
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
S1	2.64 abcd	2.65 abcd	2.48 abcde	2.37 bcde	2.64 abcde	2.70 abcd	2.33 bcde	2.58 abcde	2.61 abcde	2.65 abcde
S2	2.48 abcde	2.64 abcde	2.63 bcde	2.48 abcde	2.00 e	2.42 abcde	2.08 de	2.29 bcde	2.18 bcde	2.27 bcde
S3	0.62 g-k	0.39 h-k	0.26 i-k	0.41 h-k	1.45 f	0.91 fgk	0.85 ghi	0.48 h-k	0.21 ijk	0.75 g-j
S4	0.29 ıı-ĸ	0.15 Jĸ	0.08 ĸ	0.123 Jĸ	0.12 Jĸ	0.14 Jĸ	0.09 ĸ	0.14 Jĸ	0.12 Jĸ	0.19 Jĸ

Table 3.4 (cont.)

Osmotic stress	Genotypes									
	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20
S1	2.57 abcde	2.42 abcde	2.57 abcde	2.69 abcd	2.43 abcde	2.57 abcde	2.10 cde	2.80 ab	2.76 abc	3.07 a
S2	2.69 abcd	2.15 bcde	2.22 bcde	2.38 bcde	2.43 bcde	2.36 bcde	2.52 abcde	2.59 abcde	2.48 abcde	2.79 ab
S3	0.47 h-k	0.11 jk	0.23 ijk	1.15 fg	0.03 k	0.43 h-k	0.31 h-k	0.41 h-k	0.49 h-k	0.12 jk
S4	0.13 Jĸ	0.16 Jĸ	0.10 Jĸ	0.08 ĸ	0.04 ĸ	0.05 ĸ	0.01 ĸ	0.09 ĸ	0.06 ĸ	0.06 ĸ

Row sharing the same letters indicates non-significant differences ($S_X = 0.19$ at $p < 0.050$)

Table 3.5 Interaction effect of osmotic stress × genotype on root to shoot length ratio of durum wheat genotypes

Osmotic stress	Genotypes									
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
S1	0.72 ^{no}	0.71 ^{no}	0.76^{mno}	0.62^{o}	0.63 ^{no}	0.68 ^{no}	0.92^{k-o}	0.59^{o}	1.22 $^{i-o}$	0.62 ^{no}
S2	0.89 $^{l-o}$	0.84 $^{l-o}$	1.24 $^{i-o}$	0.74 ^{no}	1.50	1.16 $^{i-o}$	1.21 $^{i-o}$	0.92	1.21 $^{i-o}$	1.10 $^{j-o}$
S3	4.67 $^{a-f}$	4.95 $^{a-e}$	6.43 ^{ab}	3.21 $^{d-o}$	2.14 $^{f-o}$	1.70 $^{h-o}$	2.54 $^{e-o}$	3.01 $^{e-o}$	4.32 $^{a-g}$	3.84 $^{c-h}$
S4	3.50 $^{c-k}$	1.59 $^{h-o}$	3.51 $^{c-k}$	4.32 $^{a-g}$	4.82 $^{a-e}$	3.69 $^{c-i}$	4.58 $^{a-g}$	3.87 $^{c-h}$	3.97 $^{b-h}$	5.74 $^{a-d}$

Table 3.5 (cont.)

Osmotic stress	Genotypes									
	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20
S1	0.69 ^{no}	0.79 ^{mno}	0.61^{o}	0.73 ^{no}	0.80 ^{mno}	0.81 ^{mno}	0.64 ^{no}	0.71 ^{no}	0.76 ^{no}	0.65 ^{no}
S2	0.88 $^{l-o}$	1.04 $^{k-o}$	1.01 $^{k-o}$	0.94 $^{k-o}$	0.92 $^{k-o}$	1.13 $^{i-o}$	1.01 $^{k-o}$	0.73 ^{no}	0.84 $^{l-o}$	0.76 ^{mo}
S3	3.85 $^{c-h}$	3.21 $^{d-o}$	4.03 $^{b-h}$	2.05 $^{g-o}$	3.62 $^{c-j}$	5.01 $^{a-e}$	6.76 ^{a}	4.46 $^{a-g}$	4.84 $^{a-e}$	5.93 ^{abc}
S4	3.63 $^{c-j}$	2.99 $^{e-o}$	3.67 $^{d-m}$	3.93 $^{c-h}$	2.22 $^{f-o}$	2.20 $^{f-o}$	2.84 $^{e-o}$	3.25 $^{d-n}$	3.41 $^{c-l}$	2.82 $^{e-o}$

Row sharing the same letters indicates non-significant differences ($S_X = 0.73$ at $p < 0.050$)

3.3.3 Root, Shoot, Seedling Dry Weights and Root to Shoot Dry Weights Ratio

The results (Appendix 5) showed that the root, shoot, seedling dry weights and also root to shoot dry weights ratio were significantly (p <0.01) effected by osmotic stress. In addition, genotype effect for root dry weights was significant at p<0.05. In the present study the highest and lowest values for shoot dry weight were obtained from S1 and S4 treatments, respectively. Shoot dry weight decreased whilst root dry weight increased under low osmotic stress conditions (S2). However, under more severe osmotic stress conditions (S3 and S4) a remarkable decrease in root dry weights was observed. The maximum root dry weight was measured in S2 treatment whilst the minimum was observed in S4 treatment. Seedling dry weights exhibited a similar trend to shoot dry weight (Fig. 3.4). The responses of the root, shoot and seedling dry weight to osmotic stress in this study were similar to the results obtained by Jaradat and Dawayri (1981), Gawronska and Grzelok (1993), Dhanda *et al.* (2004) and Yamur and Kaydan (2008).

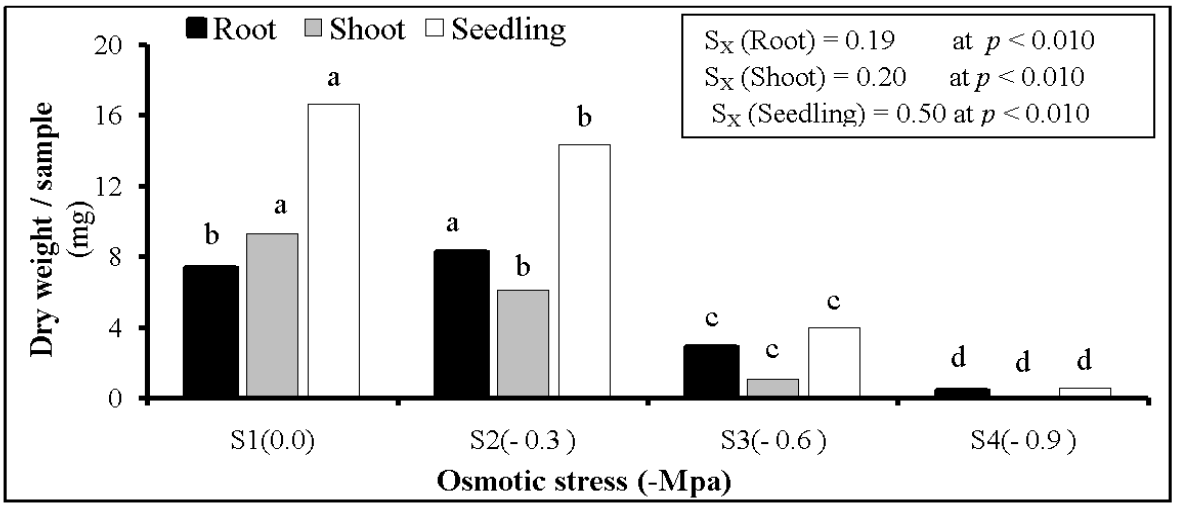

Fig. 3.4. The effect of osmotic stress on root, shoot and seedling dry weights of durum wheat genotypes

The lowest value root to shoot dry weight ratios was observed in the control treatment (distilled water) whilst the highest value was recorded in the S3 (-0.6 MPa)

treatment (Fig. 3.3). Root to shoot dry weight ratios showed similar trend with the root to shoot length ratios under control and osmotic stress conditions (Fig. 3.3).

As shown in Table 3.3, the response of the root dry weight to genotype showed that the G4 and the G10 genotypes were produced the highest values compared to all the studied genotypes. The root dry weight has been known as an important parameter in the drought tolerance (Gawronska and Grzelok 1993; Dhanda *et al.* 2004; Nazeri 2005). Hence, those genotypes with higher value of the root dry weight may be the drought tolerant genotypes.

3.3.4 Evaluation of Tolerant Genotypes to Osmotic Stress Using Stress Indices

3.3.4.1 Germination Stress Index (GSI)

The results of this study showed that germination stress index were highly significantly at p <0.01 affected by osmotic stress treatments (Appendix 5). The germination stress index (GSI) shows the ratio of germination rate under osmotic stress to normal conditions. The results indicated that with increasing osmotic stress, the germination stress index (GSI) gradually decreased from the S2 to S4 treatments. Thus the reduction of the GSI value from 92.97 in the S2 treatment to 31.41 in the S4 treatment was related to a similar decrease in germination percentage and rate, under the osmotic stress conditions (Figs. 3.1 and 3.5). It has been suggested that the germination stress index also indicates the sensitivity threshold of the cultivars and genotypes to drought stress during the germination stage Nazeri (2005) and Ghodsi (2004). The results of the germination percentage and rate showed that there were no significant difference between the S1 (distilled water) and the S2 (-0.3MPa) treatments. While, with increasing osmotic stress the germination percentage, germination rate and germination stress index significantly decreased in the S3 and S4 treatments (Figs. 3.1

and 3.5). From this we can conclude that the -0.6 MPa treatment (S3) can be the germination sensitivity threshold in these durum wheat genotypes. Similarly Ghodsi (2004) and Nazeri (2005) in separate experiments, reported that -0.6 MPa and -0.9 MPa osmotic stress levels are the germination sensitivity threshold for triticale and bread wheat cultivars, respectively.

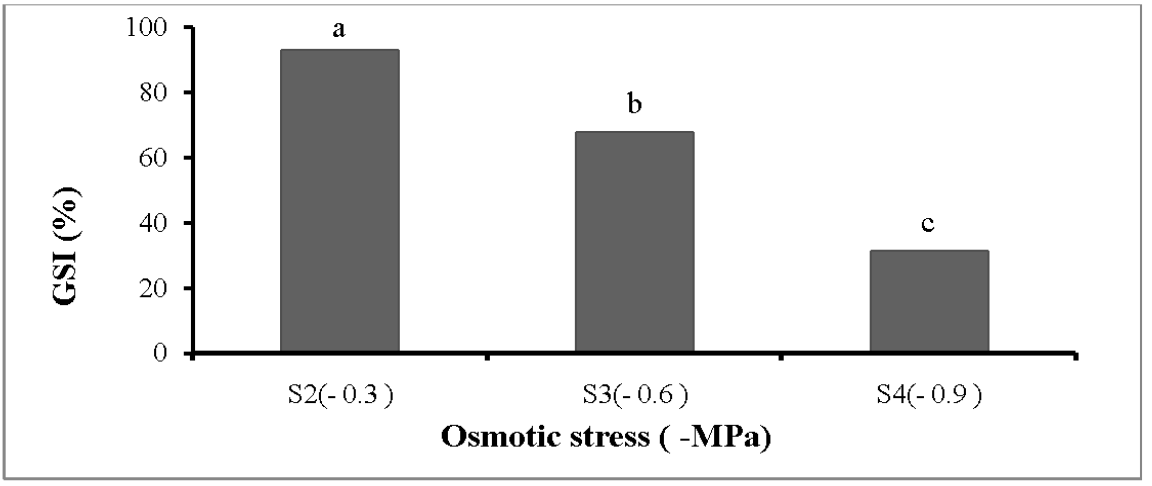

Fig. 3.5. The effect of osmotic stress on germination stress index of durum wheat genotypes

3.3.4.2 Germination Stress Tolerance Index (GSTI)

The stress tolerance index, at the germination stage, has also been used to investigate drought stress tolerance in durum and bread wheat genotypes (Fernandez 1992). Dhanda *et al.* (2004) and Nazeri (2005) suggested that root length, root and seedling dry weights are the major traits to select for studying tolerant genotypes under water stress conditions. As shown in Table 3.6 with increasing osmotic stress, GSTI decreased. However, the values depended on genotypic differences. The highest and lowest germination stress tolerance indices belonged to genotypes G4 (1.93 a) and G7 (0.8) under low osmotic stress conditions (-0.3 MPa) while G10 and G17 genotypes showed the highest (0.27) and lowest (0.01) values under severe osmotic stress (-0.9 MPa), respectively (Table 3.6). Furthermore genotypes G6 and G12 exhibited

maximum (0.90) and minimum (0.16) GSTI among the genotypes under mild osmotic stress treatment (-0.6 MPa) imployed in this study.

Table 3.6 Response of the durum wheat genotypes to germination stress tolerance index based on root dry weight under different osmotic stress conditions

Genotype	Root Dry Weight (mg)		
	S2 (-0.3)	S3 (-0.6)	S4 (-0.9)
G1	1.0 bcd	0.53 l-p	0.19 o-v
G2	0.85 c-f	0.33 p-v	0.02 u-v
G3	1.18 c-e	0.22 p-v	0.04 u-v
G4	1.93 a	0.68 j-o	0.09 s-v
G5	0.93 bc	0.72 j-n	0.05 t-v
G6	1.42 d-g	0.90 hpj	0.12 r-v
G7	0.80 d-g	0.48 m-q	0.05 t-v
G8	1.53 c-f	0.33 p-v	0.06 t-v
G9	1.18 bc	0.38 o-t	0.08 s-v
G10	1.75 bc	0.73 im	0.27 p-v
G11	1.53 fi	0.55 k-p	0.06 t-v
G12	1.27 i-k	0.16 q-v	0.10 s-v
G13	1.39 e-h	0.30 p-v	0.05 tv
G14	1.39 c-e	0.67 j-o	0.06 t-v
G15	1.59 g-j	0.43 m-r	0.03 u-v
G16	1.22 c-e	0.40 n-s	0.02 u-v
G17	1.23 i-l	0.38 o-t	0.0 1v
G18	1.34 bcd	0.36 o-u	0.04 uv
G19	1.56 e-h	0.46 m-q	0.05 t-v
G20	1.56 ab	0.46 m-q	0.02 uv

Column sharing the same letters indicates non-significant differences (p <0.05)

With regard to the GSTI obtained based on seedling dry weight, the results of study revealed that with increasing osmotic stress (from -0.3 to -0.9 MPa) germination stress tolerance index decreased in all genotypes (Table 3.7).

Table 3.7 Response of the durum wheat genotypes to germination stress tolerance index based on seedling dry weight under different osmotic stress conditions

Genotype	Seedling Dry Weight (mg)		
	S2(-0.3)	S3(-0.6)	S4 (-0.9)
G1	0.76 f-h	0.28 klm	0.08 mp
G2	0.66 g-i	0.16 l-p	0.01 p
G3	0.78 d-h	0.10 l-p	0.02 o-p
G4	1.18 ab	0.30 kl	0.04 n-p
G5	0.65 g-i	0.44 jk	0.02 o-p
G6	0.91 c-f	0.58 h-j	0.05 n-p
G7	0.55 i-j	0.24 k-o	0.01 p
G8	0.92 c-f	0.13 l-p	0.02 op
G9	0.61 h-j	0.14 l-p	0.02 op
G10	1.21 a	0.30 k-l	0.1 l-p
G11	0.99 abcd	0.25 k-n	0.03 np
G12	0.86 c-g	0.07 m-p	0.04 n-p
G13	0.77 e-h	0.11 l-p	0.02 op
G14	0.85 d-g	0.29 km	0.02 op
G15	0.98 b-e	0.16 l-p	0.01 p
G16	0.83 d-g	0.16 l-p	0.01 p
G17	0.78 d-h	0.16 l-p	0.00 p
G18	0.91 c-f	0.15 l-p	0.02 op
G19	1.06 abc	0.22 l-p	0.02 op
G20	1.14 ab	0.21 l-p	0.01 p

Column sharing the same letters indicates non-significant differences (p <0.05)

Moreover, genotypes G10 (1.21), G6 (0.58) and G10 (0.1) had the highest GSTI values under S2 (-0.3 MPa), S3 (-0.6MPa) and S4 (-0.9) osmotic stress treatments respectively. Under the same treatment conditions genotypes G7 (0.55), G12 (0.07) and G17 (0.00) showed lowest value among the twenty genotypes studied.

Table 3.8 Response of the durum wheat genotypes to germination stress tolerance index based on root length under different osmotic stress conditions

Genotype	Root Length (cm)		
	S2(-0.3)	S3(-0.6)	S4 (-0.9)
G1	0.59e-h	0.29 k-p	0.1 p-t
G2	0.66 d-g	0.18 l-t	0.05 p-t
G3	0.72 c-f	0.24 k-q	0.05 q-t
G4	0.52 g-i	0.18 l-t	0.12 r-t
G5	0.47 h-j	0.31 j-o	0.08 s-t
G6	0.57 f-h	0.36 i-k	0.1 1t
G7	0.87 bc	0.31 j-o	0.13 t
G8	0.47 h-j	0.10 q-t	0.09 q-t
G9	0.54 g-h	0.2 k-s	0.14 q-t
G10	0.55 g-h	0.18 l-t	0.24 r-t
G11	0.75 c-e	0.32 t-n	0.13 q-t
G12	0.73 c-f	0.15 n-t	0.12 r-t
G13	0.55 gh	0.10 q-t	0.11 r-t
G14	0.53 gh	0.31 j-o	0.05 p-t
G15	0.59 e-h	0.17 m-t	0.03 q-t
G16	1.11 a	0.35 j-l	0.02 q-t
G17	0.59 e-h	0.21 k-s	0.01 p-t
G18	0.74 c-f	0.21 ks	0.06 q-t
G19	0.96 ab	0.33 j-m	0.08 o-t
G20	0.82 b-d	0.18 l-t	0.05 k-r

Column sharing the same letters indicates non-significant differences (p <0.05)

As shown as Table 3.8, the response of the different genotypes to germination stress tolerance index based on root length under the different osmotic stress conditions revealed that unlike the GSTI obtained values based on root and seedling dry weights, the highest value under low osmotic stress (S2) was seen in genotype G16 with significant diference (a), while genotypes G6 and G10 exhibited maximum values for GSTI under S3 (-0.6 MPa) and S4 (-0.9 MPa) treatments, similar with the root and seedling dry weight traits.

As shown in Tables 3.6, 3.7 and 3.8, a comparison of the genotype responses to germination stress tolerance index, based on root length, root dry weight and seedling dry weight, showed that the G6 and G10 genotypes had the highest GSTI value based on all of the calculated traits under mild (S3) and severe (S4) osmotic stress conditions. However the highest GSTI value under lower stress conditions (S2) belonged to different genotypes (G4, G10 and G16).

Many researchers, such as Khan *et al.* (2002), Nazeri (2005), Dhanda *et al.* (2004) and Ghodsi (2004), Okçu *et al.* (2005), Rauf *et al.* (2007) and Yamur and Kaydan (2008) reported the important and significant relationship between root and seedling dry weight with germination percentage, germination rate, root length, and shoot dry weights in response to the drought tolerance as is the case in the present study. The higher values observed in some genotypes (Tables 3.6, 3.7 and 3.8) can be related to the root to shoot length ratio, where the genotype G10 showed the highest root to shoot length ratio among all the genotypes under severe osmotic stress condition. This finding supports the results of Radhouane (2007) that genotypes exhibiting longer root length under water limitation show an adaptive reaction to increase water uptake ability by the seeds.

3.3.5 Correlation among Different Traits at Germination Stage

Correlation among different traits showed that the highest correlation coefficient was calculated between seedling dry weight and shoot dry weight and also between seedling dry weight and root dry weight (r = 0.96** and r = 0.95**). The lowest correlation coefficient was seen between germination percentage and root to shoot length ratio (r = - 0.85**). In the present study the germination percentage and rate showed a positive and highly significant correlation with coleoptiles length, root length, shoot length, root, shoot and seedling dry weights. Root and shoot lengths also showed positive and highly significant correlation with coleoptiles length, root dry weight, shoot dry weight and seedling dry weight. However, they exhibited a negative and highly significant correlation with root to shoot length ratio and root to shoot dry weight ratio. Dhanda *et al.* (2004) showed that under drought conditions, genotypes with strong root growth are particularly important in tolerating drought. With regard to coleoptiles length, the results were similar with reports of Ghodsi (2004) and Rauf *et al.* (2007). There was a negative and highly significant correlation between root to shoot length ratio with root, shoot and seedling dry weights. Root to shoot length ratio showed a positive and highly significant correlation with shoot to root dry weight ratio. The highest and lowest correlation coefficient for root to shoot length ratio was observed with germination rate (r = - 0.22**) and germination percentage (r = - 0.85**). It can be seen that the effects of severe osmotic stress on decreasing shoot length was more than its effect over decreasing root length (Table 3.9). the relationship between the germination traits of the different durum wheat genotypes under osmotic stress conditions have also been reported by Khan *et al.* (2002), Nazeri (2005), Dhanda *et al.* (2004), Ghodsi (2004), Okçu *et al.* (2005), Rauf *et al.* (2007), Yamur and Kaydan (2008).

Table 3.9 Correlation coefficient among germination percentage (G%), germination rate (GR), coleoptiles length (CL), root length (RL), shoot length (SL), root dry weight (RDW), shoot dry weight (SDW), seedling dry weight (SLDW) of the various durum wheat genotypes in the germination and seedling stage under the osmotic stress condition.

Traits	G%	GR	CL	SL	RL/SL	RDW	SDW	SLDW	RDW/SDW
G%	1	0.53**	0.68**	0.58**	-0.85**	0.70**	0.60**	0.68**	0.57**
GR		1	0.60**	0.54**	-0.22**	0.62**	0.58**	0.62**	-0.13**
CL			1	0.88**	-0.45**	0.89**	0.90**	0.93**	-0.20**
SL				1	-0.43**	0.77**	0.95**	0.90**	-0.25**
RL/SL					1	-0.36**	-0.47**	-0.42**	0.47**
RDW						1	0.84**	0.95**	-0.1**
SDW							1	0.96**	-0.28**
SLDW								1	-0.21**
RDW/ SDW									1

* Significant difference at $p < 0.05$ ** Significant difference at $p < 0.01$

3. 4 CONCLUSIONS

The germination percentage, coleoptiles length, root length, shoot length, shoot and seedling dry weight decreased with increasing osmotic stress, whereas root to shoot length ratio and root to shoot dry weight ratio increased by increasing osmotic stress. In addition, germination rate and root dry weight increased from control (distilled water) to -0.3 MPa treatment, while their values decreased with increasing the severity of the osmotic stress (-0.3 to -0.9 MPa). The highest correlation coefficient among different traits was calculated between seedling dry weight and shoot dry weight. The overall results showed that with increasing osmotic stress, the GSTI decreased significantly. Hence, the highest and lowest value for GSTI was observed in low (-0.3 MPa) and severe (-0.9 MPa) osmotic stress treatments. Besides, the germination sensitivity threshold was determined as -0.6 MPa osmotic stress treatment based on GSI and germination rate. The comparison between the GSI and GSTI revealed that the results obtained due to screening in the tolerant genotypes were considerably similar for both of the indices employed. For this purpose, the promising durum wheat genotypes RASCON- 39/TILO - 1 and RASCON - 37/BEJAH - 7 were screened as the most tolerant genotypes under low and severe osmotic stress whereas GARAVITO - 3/RASCON- 37 // GREEN - 8 and HAI - OU - 17/ GREEN - 38 exhibited the lowest GSTI value under osmotic stress conditions.

CHAPTER 4

WATER DEFICIT-INDUCED CHANGES ON PHYSIOLOGICAL TRAITS OF DURUM WHEAT GENOTYPES

4.1 INTRODUCTION

The availability of sufficient water during the growth and development stage of a crop is important for achieving maximum productivity. It is well documented that the availability of water for plant growth is a key aspect determining plant distribution in natural ecosystems and is the single most important limiting factor in agricultural systems (Semenov *et al.* 2009). However, conditions such as insufficient precipitation, soil with low water holding capacity, extreme temperatures or a combination of these factors can restrict moisture availability to the plant (Elavarthi 2005). Stress is the altered physiological condition in plants brought about by factors that tend to alter their chemical and physical balance (Shao *et al.* 2008).

Among abiotic stresses, water deficit, is the most unfavorable factor in plant growth and production simply because a plant is made up of mostly water. However, the different physiological responses of plants to water limitation usually change with the severity as well as with the duration of water deficit. Water deficit manifests itself in plants through decreasing total water potential, water content, turgor, closure of stomata, and reduction of the cell enlargement and growth. It reduces various physiological and biochemical processes, such as photosynthesis, respiration translocation, carbohydrates, nutrient metabolism, and hormones. In order to survive, under water deficit conditions, plants have developed mechanisms to cope with this stress (Blum 1996; Chaitanya *et al.* 2003; Bhatt and Rao 2005; Elavarthi 2005).

Mwanamwenge *et al.* (1999) and Morant- Manceau *et al.* (2004) reported that water deficit significantly reduced net photosynthesis in flag leaf and also terminal internodes in wheat. They also reported that with decreasing net photosynthesis, the transpiration rate, which was dependent on stomatal closure, decreased under water deficit conditions. Moever, when plants are exposed to water deficit conditions at grain

filling, leaf rolling reduces the effective leaf area, which would explain the reduction in photosynthesis and transpiration. In addition to the decreased photosynthetic efficiency, water deficit can pose injurious influences on plant yield such as when the photosynthetic products temporarily stored in vegetative organs are being translocated to grain to compensate for the lower production photosynthetic carbon products.

Intercepted photosynthetically active radiation (PARI), leaf area index (LAI), light extinction coefficient (k) and radiation use efficiency (RUE) are major canopy characteristics in grain crops. However, it has been reported that amongst these major canopy characteristics, PARI is the main factor determining crop growth in wheat. In addition to this, the successful modeling of plant growth has been established on based on data from the leaf area index, light extinction coefficient for PARI and RUE. However, most of the information reported on these major canopy characteristics have been made under optimum moisture conditions in field experiments for different wheat varieties (Kiniry *et al.* 1989; Siddique *et al.* 1989; Gregory *et al.* 1992; Abbate *et al.* 1997).

Liang and Richards (1994) reported that rapid extension of the green leaf area index in the early growth and developmental stages results in a better establishment of the plant in the soil. It suggested that suitable plant cover in the early stages of growth can decrease evaporation of water from the soil surface. Their results indicated that rapid extension of the barley leaves area after emergence could be a strong reason for more tolerance to drought compared to wheat varieties under water deficit conditions. However many studies have reported that there is a reduction of the leaf area index (LAI) in the early growth and developmental stages (limitation water before terminal spikelets) under water deficit and unavailable water conditions, which will pose a problem to crop productivity (Robertson and Giunta 1994; Richards 1996; Nazeri 2005). Findings of Reynolds *et al.* (2000) and Araus *et al.* (2002; 2003) working on

wheat and Nazeri (2005) on triticale, showed a positive correlation between green leaf area index (LAI) and radiation interception with grain yield for new varieties during grain filling. These workers observed decreasing LAI during grain filling due to water deficit conditions.

Several researchers have studied the light extinction coefficient (k) and radiation use efficiency (RUE) based on photosynthetically active radiation (PAR) in different plants. A range of different values have been reported for the light extinction coefficient based on PAR for cereals. It varies from 0.41 to 0.66 for barley and 0.37 to 0.82 for wheat. While radiation use efficiency ranged from 1.79 to 2.33 g MJ^{-1} for barley and 1.46 to 2.93 g MJ^{-1} for wheat under optimum water conditions (Gregory *et al.* 1992; Goyne *et al.* 1993; Calderini *et al.* 1997; O'Connell *et al.* 2002). In contrast to this, Muurinen and Peltonen-Sainio (2006) reported that the RUE values were similar for both barley and wheat.

It has been reported that radiation use efficiency (RUE) might be affected by vapor pressure, water stress and nutrient availability (Jamieson *et al.* 1995; Ple´net *et al,* 2000; Kemanian *et al.* 2004) even though RUE remains relatively stable during the crop growth period under optimum irrigation. They observed that under water deficit conditions, the radiation use efficiency was reduced, particularly during grain filling.

Cumulative dry matter in the presence of water stress depends on the green leaf area index and canopy radiation interception values. The results of Robertson and Giunta (1994) and Ghodsi (2004) on wheat, Legg *et al.* (1979) on barley, Martyniak (2002) and Nazeri (2005) on triticale, showed that cumulative dry matter reduced significantly under water deficit conditions during the terminal spikelets and physiological maturity stages.

Results from previous studies have shown that the reduction of photosynthesis and the acceleration of leaf senescence, due to water deficit during the grain filling

stage, have been the major cause for reducing grain yield in wheat (Kobata *et al.* 1992; Palta *et al.* 1994). The increase in demand for pre-anthesis carbon reserves could be due to reduction of the photosynthesis at the same stage. Subsequent studies have shown that water limitation during grain filling significantly increases the contribution of pre-anthesis assimilates from stems, leaves and sheaths to grains (Kobata *et al.* 1992; Yang *et al.* 2000; Foulkes *et al.* 2002). Plants have different strategies and mechanisms for survival and growth under water deficit conditions or maintaining available water by reducing leaf size, regulating stomatal closure and improving the root system to reach and uptake more water from the soil. Researchers have discovered that these strategies have improved tolerance in plants, which have resulted in maintaining their productivity despite the water deficit conditions (Richards *et al.* 2002; Condon *et al.* 2004; Collins *et al.* 2008).

The objectives of this research are:

1. To study the growth parameters and physiological traits of selected durum and bread wheat genotypes under different irrigation regimes.
2. To investigate the effects of water deficit on the accumulation of dry matter during different growth and developmental phases.
3. To determine the intercepted photosynthetic active radiation and radiation use efficiency in the different genotypes under water deficit conditions.

4.2 MATERIALS AND METHODS

4.2.1 Field Experimental Setup

The study was conducted during the 2007-2008 growing season at the Khorasan-e- Razavi Agricultural and Natural Resource Research Center, Iran. The field experiments were laid out in Mashhad (36°, 13′ N latitude and 59°, 40′ E, elevation 985 m) research station with a split plot design based on a complete randomized block design including three replications. Irrigation regime was considered as the main plots and included four levels: I1, optimum irrigation; I2, water limitation from one- life to floral initiation stage; I3, water limitation from floral initiation to anthesis and prevention of precipitation using a mobile rain shelter during this period; I4, water limitation after anthesis and prevention of precipitation using a mobile rain shelter. The growth and developmental stages (from emergence to maturity) was considered in the main plots. In adition, total amounts of irrigation water used and their frequency for each main plat (7.2 m^2) were 5.54 m3 (7 rrigation periods, including rainfall), 3.27 m^3 (4 irrigation periods, including rainfall), 3.24 m^3 (5 irrigation periods, including rainfall) and also 3.24 m^3 (5 irrigation periods, including rainfall) in I1, I2, I3 and I4 irrigation treatments across plantig to harvesting, respectively. However, prevention of precipitation in the reproductive and grain filling stages was done for calculating the effect of waterdeficit on crop characteristics by cutting the irrigation, without the effect of rainfall. Therefore, the amonts of irrigation water used were similar values during the reproductive and grain filling.

Sub-plots were assigned to four promising durum wheat genotypes inclouded: G1, HAI - OU- 17 / GREEN - 38; G2, RASCON - 37 / BEJAH - 7; G4, RASCON - 39 / TILO - 1; G5, GARAVITO3 / RASCON37 // GREEN8 and a bread wheat cultivar (G3, Chmran) which has been released as a drought tolerant variety for planting in arid

and semi- arid regions (Ghodsi 2004). The durum wheat seeds were obtained from the elite durum yield trials (2006 -2007) in the Seed and Plant Improvement Institute (SPII) Iran, which were tested under different osmotic stress conditions using polyethylene glycol (PEG 6000). According to the results of laboratory experiments on germination and seedling growth explained in chapter 3, four durum wheat genotypes were screened based on stress tolerance indices. Amongst the genotypes RASCON-37/BEJAH-7 and RASCON-39/TILO-1 were assigned in the subplot as severe (G2) and moderate (G4) drought tolerant genotypes while HAI-OU-17 / GREEN-38 and GARAVITO3 / RASCON37 // GREEN8 were applied as susceptible durum wheat genotypes (G1and G5). In addition to these, Chamran bread wheat (G3) was put-upon as an identified drought tolerant cultivar in sub-plots to compare the drought tolerance traits amongst genotypes studied (Appendix 6).

According to the results of the Soil and Water Research Department (Keshavarz *et al.* 2006) the classifications of soil was Fine- Loamy over Sandy- Skeletal, Mixed, Mesic at the Mashhad experimental site. In addition, soil pH and EC (dS m^{-1}) were measured as approximately 8.0 - 8.1 and 1.7 - 2.2, respectively (see Appendix1).

Before sowing, the field was fertilized with 50, 90 and 50 kg NPK ha^{-1}, respectively. Additionally, 70 kg N was top-dressed and split into two applications. To prevent the occurrence of diseases, seeds were coated with Vitavax fungicide (Carboxin Thiram) which was used at 2 g kg^{-1} seed before planting. Moreover, weeds were chemically controlled by 2, 4-D (2, 4-dichlorophenoxyacetic acid) at the end the tillering stage by 2 L ha^{-1}. Additionally, all the other weeds were removed manually during booting to anthesis. Each plot consisted of 12 rows 3 m in length and spaced 20 cm apart. Therefore, the subplot size was calculated as 7.2 m^2 ($12 \times 3 \times 0.2$) and the seed density was 450 seeds m^{-2} based on 1000-grain weight.

4.2.2 Measurements

4.2.2.1 Growing Degree Days (GDD) Determination

Daily meteorological data were obtained from Mashhad Climatology Synoptic Research Station, which was located about 2 km from the field experiments and were used to calculate heat units expressed as growing degree days (GDD) accumulated during growth and developmental stages for each developmental period in the different treatments. A growing Degree Day is equivalent to thermal time as defined by Mosseddaq *et al.* (2005). Daily GDD was calculated by using the formula:

$$GDD = [(T_{max} + T_{min}) / 2] - T_b$$

Where, T_{max} is maximum air temperature (°C) for the day, T_{min} is minimum air temperature, and T_b is the base temperature, which was 0°C, for bread and durum wheat genotypes. When the mean daily temperature was more than 30°C or less than zero, a heat unit value of 30 and 0 were assigned for T_{max} and T_{min}, respectively as in Ghodsi (2004).

4.2.2.2 Cumulative Dry Matter and Growth Parameters Determination

In order to compute the accumulated dry matter and growth parameters based on growing degree days, the above ground biomass were determined by cutting plants of three rows per plot, 0.5 m length by 0.2 m spacing (0.3 m^2) in each plot during the different growth and developmental stages, namely, the two-leaf, booting, terminal spikelets, anthesis, soft dough and physiological maturity stages. Total leaf area in each sample was measured using a leaf area meter (model Delta-T) during the stated six growth and developmental stages. The samples were kept separately in an incubator for 3 days at 80 °C to dry them to a constant the weight and finally the dry weight determined. The different growth parameters were calculated according to Causton and Venus (1981) and Patterson (1993), as follows:

$$LAI = LA\ area / LA\ ground$$

$$CGR = W_n - W_{n-1} / GDD_n - GDD_{n-1}$$

$$RGR = (Ln\ W_n - Ln\ W_{n-1}) / GDD_n - GDD_{n-1}$$

$$NAR = [(W_n - W_{n-1})(Ln\ LA_n - Ln\ LA_{n-1})] / [(GDD_n - GDD_{n-1})(LA_n - LA_{n-1})]$$

where LAI ($m^2\ m^{-2}$), CGR (mg $m^{-2}\ d^{-1}$), RGR (mg $g^{-1}\ d^{-1}$), NAR (mg $m^{-2}\ d^{-1}$) are leaf area index, crop growth rate, relative growth rate, net assimilation rate, respectively. In addition, W_n and W_{n-1} are the total dry mass at the different growth degree-days (GDD_n and GDD_{n-1}) from the measured leaf area values (LA_n and LA_{n-1}).

4.2.2.3 Radiation Use Efficiency (RUE)

Photosynthetically active radiation (PAR 400 –700 *m*mol $m^{-2}\ s^{-1}$) was measured above and beneath plant canopies with a Sun Scan Canopy Analysis System (Model SSI-UM-1.05) which had a reference quantum sensor (RQS) for measuring direct and diffuse radiation above the canopy and also a linear quantum sensor (Sun Scan probe 1 m long) for measuring PAR beneath plant canopies. The RQS sensor was placed at the top of plant canopies in order to record incident radiation (I°) and the linear quantum sensor was set between the crop rows at the soil surface to record transmitted radiation (I). Measurements were taken on clear days during the 2 h period around solar noon, from three separate places per plot, with replications. The data obtained were averaged and used for further calculations of radiation interception (RI) and extinction coefficient (k), according to Sinclair and Muchow (1999) and Fisher (2001) as follows;

$$I\% = [1 - (I / I_{\circ})] \times 100$$

$$K = [Ln\ (I / I_{\circ})] / LAI$$

Cumulative radiation intercepted by plants was calculated using the solar radiation data from the Climatology Station. The formula is shown below.

$$PAR_{\circ} = (I_{\circ}) \times 0.48$$

$$PARI = PAR_{\circ} \times [1\text{-}\exp(-k \times LAI)] \times 0.95$$

In these formula, $PAR_{\circ}$ and PARI are photosynthetically active radiation above the canopy (incoming) and photosynthetically active radiation interception (MJ m^{-2} day^{-1}) respectively. With regard to the importance of the radiation intercepted which is converted into dry matter in plants, the radiation use efficiency (g MJ^{-1}) was calculated from the data obtained according to the Sinkler and Mochave (1999) formula:

$$RUE = (W_n - W_{n-1}) / (PARI_n - PARI_{n-1})$$

$$GY = RAD \times RI\% \times RUE \times HI$$

where W_n and W_{n-1} are shoot biomass dry weight at the different days (n and n-1) and $PARI_n$, $PARI_{n-1}$, GY, RAD, HI, BY, are intercepted photosynthetically active radiation at time n and n-1, grain yield, total radiation intercepted by plants during the growth stage, harvest index and biological yield, respectively.

4.2.3 Data Analyses

For all the investigated physiological parameters, analysis of variance was statistically performed according to the split-plot arrangement based on a complete randomized block design using MSTAT-C and SPSS software packages. Significant differences among the mean values were compared via the Duncan's Multiple Range Test ($p < 0.05$ and $p < 0.01$).

4.3 RESULTS AND DISCUSSION

4.3.1 Cumulative Dry Matter (CDM)

An analysis of variance on the cumulative dry matter (CDM) during different growth and developmental stages revealed that it was highly significant (p <0.01) on the CDM at the double ridge, terminal spikelets, booting, soft dough and physiological maturity stages, although the irrigation regime effect was not significant on the CDM at the two-leaf stage. Besides this, the effect of irrigation regimes, the interaction effect of water deficit and genotype were also significant (p <0.05) on the CDM at the anthesis stage, double ridge and terminal spikelets stages (see Appendix 7).

4.3.1.1 Cumulative Dry Matter Trend under Different Irrigation Regimes

Cumulative dry matter values during the different growth and developmental stages for the different irrigation regimes and genotypes are summarized in Table 4.1 studied. Apart from the two-leaf stage, the highest CDM values for each growth and developmental stages was observed under optimum irrigation condition (I1), while water limitation until floral initiation (I2) caused the biggest reduction in dry matter values (168 g m^{-2}). Adequate early season rainfall caused no significant differences in dry matter amongst the different irrigation regime treatments at the two-leaf stage (Appendix 2). The early season water deficit (negative effect) from one-leaf to floral initiation (I2) affected accumulation of dry matter remarkably at all the growth stages. A comparison of the cumulative dry matter between the optimum irrigation (I1) and I2 treatments showed a reduction, for the I2 treated plants, of 24% at double ridge, 31% at terminal spikelets, 39% at booting, 33% at anthesis, 31% at soft dough and 26% at physiological maturity. This reduction in dry matter under water deficit conditions

compared to normal irrigation in the early season is concurrent with the findings of Legg *et al.* (1979) on barley, Robertson and Giunta (1994), Giunta *et al.* (2004) on wheat and Martyniak (2002) and Nazeri (2005) on triticale.

There were no significant difference between the irrigation treatments of I3 (water limitation from the floral initiation to anthesis) and I4 (water limitation from anthesis to grain filling) for total dry matter during the different growth and developmental stages The cumulative dry matter in the terminal spikelets at I3 treatment decreased by 16% compared to optimum irrigation, while the reduction was only 7% in the I4 treatment (Table 4.1)..

Water limitation during the post anthesis period (I4) also decreased the cumulative dry matter by 16% compared to optimum irrigation (I1) at the soft dough and physiological maturity stages (Table 4.1). The reduction of dry matter in the I4 treatment (post anthesis) is probably the result of decreasing grain yield under drought stress conditions at the post anthesis period. Thus, a reduction in dry matter occurred during the grain-filling period under water deficit and consequently reduced the intercepted photosynthetically active radiation (Fig. 4.10). These results concurred with the finding of Martyniak (2002) and Nazeri (2005) on triticale and Fisher (2001) and Ghodsi (2004) on wheat.

Table 4.1 Effects of the different irrigation regimes and genotype on cumulative dry matter (CDM) at the different growth and developmental stages

Treatments	Cumulative Dry Matter (g m^{-2})						
	Two-leaf	Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
I1	94.20 a	220.8 a	372.3 a	763.9 a	1058 a	1281 a	1370 a
I2	90.20 a	168.7 b	256.6 c	461.3 c	732.5 b	865.3 c	1011 c
I3	89.67 a	203.1 a	314.5 b	597.9 b	919.3 a	1007 b	1108 bc
I4	93.67 a	210.5 a	347.1 a	636.7 b	984.1 a	1083.1 b	1171 b
LSD	9.84	33.58	31.52	55.80	176.6	113.30	115.70
Sx	3.58	6.40	6.01	10.64	51.03	21.60	22.07
Genotype							
G1	89.58 cd	195.8 b	319.6 b	609.1 ab	902.8 ab	1045 a	1205 a
G2	93.58 b	197.8 b	320.5 b	622.9 a	940.4 a	1081 a	1219 a
G3	97.92 a	233.3 a	355.4 a	629.6 a	937.8 a	1062 a	1204 a
G4	91.67 bc	196.3 b	316.7 b	621.9 a	938.7 a	1076 a	1213 a
G5	86.92 d	181.8 b	301.8 b	591.3 b	898.1 b	1033 a	1181 a
LSD	3.391	22.33	22.54	28.50	36.34	48.89	40.22
Sx	1.416	5.763	5.821	11.90	15.17	20.41	16.79

Column sharing the same letters indicates no significant differences (at $p < 0.01$)

Accumulation of dry matter, which is indicator for transformation of the radiation into biomass in plants, can be a function of the leaf area index and intercepted radiation by the plant canopy (Robertson and Giunta 1994; Reynolds *et al.* 2000). Consequently, an increase in the leaf area index (Table 4.2 and Fig. 4.3) and the percentage of intercepted radiation (Table 4.6 and Fig. 4.10) increased the cumulative dry matter during the growth and developmental stages under optimum irrigation conditions. The results were in agreement with Liang and Richards (1994) who reported that rapid extension of the green leaf area index in the early growth and developmental stages established the plant better in the soil. Thus, suitable plant cover in the early stages of growth can decrease evaporation from the soil surface.

The above results also shows that a reduction in dry matter during the early season water deficit condition (I2), in comparison to optimum irrigation, reduced the cumulative dry matter in the later developmental stages. This makes available moisture in the early growth and developmental stage an important and vital factor for avoiding dry matter reduction during the more advanced growth stages. In the other words, even further irrigations after water limitation during two-leaf to double ridge stage could not recover the cumulative dry matter production in all the other subsequent stages. This mean that, due to severe competition between spike growth and stem elongation, for photosynthetic assimilates during the double ridge till anthesis stage, a reduction in the production of photosynthetic products can severely hamper spike growth. This has been reported to reduce yield and yield components in crops (Reynolds *et al.* 2000).

As shown as Fig. 4.1, the pattern of dry matter accumulation according to cumulative growth degree-days (GDD) across the growth and developmental cycles exhibited an incremental trend under optimum and water deficits conditions. However, the highest and lowest accumulated dry matter, in each developmental stage, belonged to optimum irrigation and I2 water deficit treatment, respectively. In addition, the cumulative dry matter mean values under the mean of the irrigation regimes showed a slightly sigmoidal curve. With the accumulation of the growth degree-days from early to late growth and developmental stages, the total dry matter showed an increase of 2%, 4%, 8%, 14%, 21%, 24% and 27% at two-leaf , double ridge, terminal spikelets, booting, anthesis, soft dough and physiological maturity stages, respectively (Fig. 4.1).

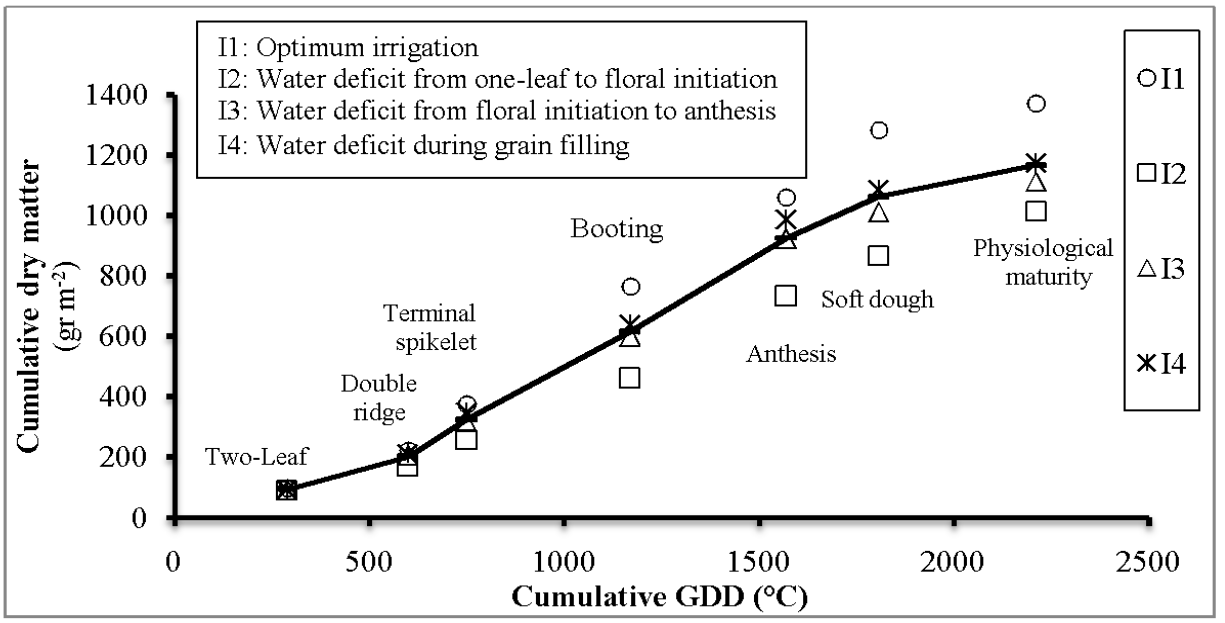

Fig. 4.1. Trend cumulative dry matter at growth and developmental stages under different irrigation regimes

4.3.1.2 Accumulation of Dry Matter during Growth Stages in Different Genotypes

As shown in Table 4.1, apart from the soft dough and physiological maturity stages which did not exhibit any significant differences among the different genotypes studied (G1, G2, G3, G4 and G5) for the total cumulative dry matter, there were significant differences among them at two-leaf, double ridge, terminal spikelets, booting and anthesis stages. The highest accumulation of dry matter belonged to the G3 (drought tolerant bread wheat) genotype at two-leaf (97.9 g m^{-2}), double ridge (233 g m^{-2}), terminal spikelets (355 g m^{-2}), booting (629.6 g m^{-2}) growth and developmental stages. However, the G2 genotype (durum wheat) exhibited values almost similar to that of G3 at the same stages. Besides this the accumulation of dry matter from anthesis to physiological maturity was higher in the G2 genotype than in the G3 genotype. It increased to 1081 g m^{-2} in G2 at the soft dough stage, whilst for the G3 genotype it was 1062 g m^{-2} at the same stage. The lowest dry weight values were recorded in the G5 (durum wheat) genotypes in all the stages of growth compared to others genotypes.

It has been documented that successful wheat varieties have a high stem reserve capacity for accumulating photosynthetic carbohydrates under optimum and water deficit conditions (Blum 1996; Plaut *et al.* 2004; Kirigwi *et al.* 2004). In addition, the translocation of considerable quantity of the stem-reserved carbohydrates to the grains is a very important factor during grain filling (Rawson *et al.* 1983; Gent 1994). The results of the current study on the cumulative dry matter at different growth and developmental stages have shown that the G2 and G3 genotypes possess characteristics that are highly favorable under water stress conditions compared to all the others genotypes studied.

As shown in Fig. 4.2, the pattern of dry matter accumulation according to the cumulative growing degree-days (GDD) during the growth and developmental cycles exhibited a sigmoid curve with an incremental trend for the different durum and bread wheat genotypes (Fig. 4.1). However, differences in dry matter values between the highest and lowest in each stage were small. This indicates that the effect of the different irrigation regimes on the cumulative dry matter was more than the genotypic effects.

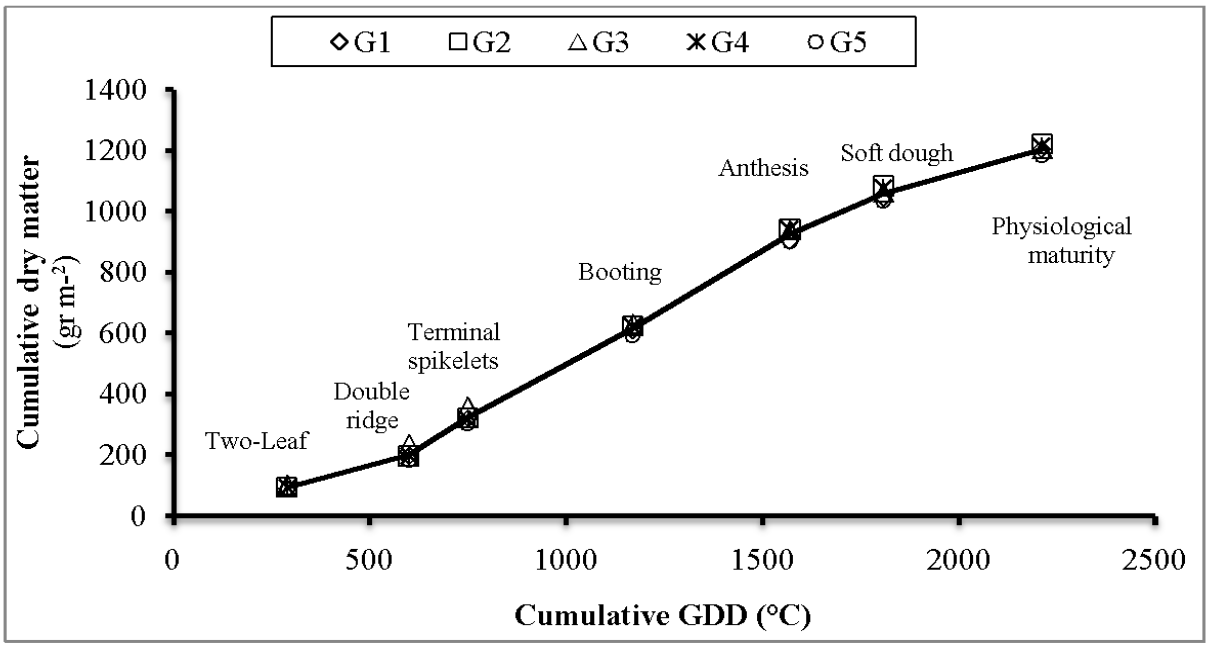

Fig. 4.2. Trend cumulative dry matter at growth and developmental stages of different genotypes

4. 3.2 Growth Parameters

Crop growth analyses is the interpretation of changes in plant mass or size through a specified phase of time and usually reflects the amount of growth during a specified period. It is an outcome of the rate of growth and duration of the period (Gardner *et al.* 1985). The growth parameters normally employed in studies in plants under drought stress includes, leaf area index (LAI), crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (NAR) (Simane *et al.* 1993; Chandrasekhar *et al.* 2000). These are reported below for the different irrigation regimes and genotypes studied.

Table 4.2. Effect of irrigation regimes and genotype on leaf area index (LAI) in different growth and developmental stages of durum and bread wheat genotypes

	Leaf Area Index						
Treatments	Two-leaf	Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
Irrigation regimes							
I1	0.96 a	1.46 a	2.27 a	3.45 a	4.35 a	3.59 a	2.79 a
I2	0.36 b	0.86 b	2.03 bc	3.19 b	3.82 c	2.61 b	2.24 b
I3	0.95 a	1.44 a	1.97 c	3.29 ab	4.21 ab	2.96 b	2.73 a
I4	0.91 a	1.41a	2.24 a	3.38 ab	4.11 b	2.81 b	2.26 b
LSD value	0.20	0.19	0.19	0.21	0.19	0.58	0.43
Sx	0.04	0.07	0.07	0.04	0.04	0.17	0.12
Genotypes							
G1	0.67 a	1.17 ab	2.05 a	3.29 a	4.07 b	2.92 bc	2.45 bc
G2	0.80 a	1.30 a	2.07 a	3.39 a	4.44 a	3.43 a	2.90 a
G3	0.53 a	1.03 b	2.13 a	3.47 a	4.38 a	3.26 ab	2.77 ab
G4	0.80 a	1.30 a	2.14 a	2.87 b	3.85 b	2.63 c	2.17 c
G5	0.85 a	1.35 a	2.19 a	3.36 a	3.87 b	2.73 c	2.24 c
LSD value	0.38	0.17	0.14	0.24	0.22	0.39	0.40

Column sharing the same letters indicates no significant differences (at $p < 0.01$)

4.3.2.1 Leaf Area Index (LAI)

An analysis of variance on the leaf area index (LAI) during the different growth and developmental stages showed that the effect of the different irrigation regimes was not significant on the LAI at the terminal spikelet stage, but it was highly significant (P <0.01) on the LAI at the two-leaf, double ridge, booting and anthesis stages. Besides this, the effect of the irrigation regimes was also significant (p <0.05) on the LAI at the post anthesis (soft dough and physiological maturity) stages. On the other hand, the genotypic effects on the leaf area index was highly significant (p <0.01) for all the growth and developmental stages except at the two-leaf and terminal spikelet stages. Interaction effect of irrigation regime and genotype on the LAI was highly significant (p <0.01) at the booting, anthesis, soft dough and physiological maturity stages (Appendix 8).

4.3.2.1.1 Effect of Different Irrigation Regimes on the Leaf Area Index (LAI)

As shown and summarized in Table 4.2, the leaf area index (LAI) indicated the highest values under I1 irrigation treatment (optimum irrigation) in all the growth and developmental stages compared to the water deficit conditions. Among water deficit treatments, water limitation during the one-leaf to double ridge stage (I2) exhibited the lowest leaf area index compared to the other irrigation regimes. In addition, the negative effects of the early season water deficit (I2) in reducing the LAI, compared to the control in each growth stages, continued until physiological maturity. The biggest difference in LAI was observed at the soft dough stage between the optimum irrigation treatment with values of 3.59 and the I2 water deficit treatment with values of 2.61. On the other hand, there were no significant differences between optimum irrigation and I3 water deficit treatments at the two-leaf and double ridge stages. There were also no significant differences in LAI between the optimum irrigation and I4 water deficit treatments during from two-leaf to booting stage. The optimum irrigation regimes

during planting date and double ridge in I3 and through planting date to anthesis in the I4 treatments had caused no significant difference for LAI values in those explained stages. It is known that leaf area extension in the early growth and developmental stage is the first process that will be affected by water deficit which will cause a reduction in the leaf area index (Boyer 1970; Bradford 1990). Hence, the LAI reduction can reduce grain yield when the crop undergoes early water limitation conditions. In addition, rapid leaf area extension in the early growth stage can cause better establishment of the plant in the soil. Consequently, it prevents the evaporation of water from the soil surface, which is a very important factor to overcome drought at the early season water deficit conditions (Robertson and Giunta 1994; Chandrasekhar *et al.* 2000). The reduction in the LAI during the early water deficit treatment (I2) in this study which resulted in further reduction in the leaf area index at the subsequent growth and developmental stages concurs with the findings of the above researchers.

As shown in Table 4.2, water limitation during the double ridge to anthesis (I3) stage reduced the LAI when compared to the control (optimum irrigation) in each stage from the terminal spikelet to physiological maturity. The reduction in LAI values was significantly different at the terminal spikelet and soft dough stage for the I1 and I3 treatments. LAI were 2.27 and 1.97 under the I1 and I3 treatments at the terminal spikelets stage and 3.59 (I1) versus 2.96, respectively at the soft dough stage. With regard to the formation of the spike structure during the time of the double ridge to anthesis stage (I3 irrigation regime condition), any negative effect at this period causes a similar impact on the spike traits. Reduction of the LAI under water deficit condition also decreases intercepted radiation (Fig. 4.10). These results are in agreement with the findings of Fisher (2001) and Araus *et al.* (2002; 2003).

Water deficit during anthesis to physiological maturity (I4) significantly decreased LAI when compared to the LAI values at optimum irrigation at the anthesis,

soft dough and physiological maturity stages. The biggest difference in leaf area index between the optimal condition and I4 treatment was observed at the soft dough stage. Additionally, the highest value at that stage was 3.59 under normal irrigation, while the lowest was recorded in the I4 (2.81) treatment (Table 4.2). It is well documented that water deficit during grain filling causes rapid senescence and leaves losing their green colour and subsequently plants being defoliated, which could be compared to the reduction of the leaf area index under water limitation (L4) treatment. The reduction of the leaf area index during grain filling under I4 deficit water treatment reduced intercepted photosynthesis active radiation under compared to optimum irrigation (Figs. 4.3, 4.9 and 4.10). A decrease in absorptive radiation by the plant canopy during this period will cause a negative effect directly on the grain yield (Fig. 6.7). This is in agreement with the findings of Reynolds *et al.* (2000), Araus *et al.* (2003; 2004) on wheat, Mosaad *et al.* (1995) and Chandrasekhar *et al.* (2000) on durum wheat and Nazeri (2005) on triticale. They observed a positive correlation between leaf area index and intercepted photosynthetic radiation by the plants.

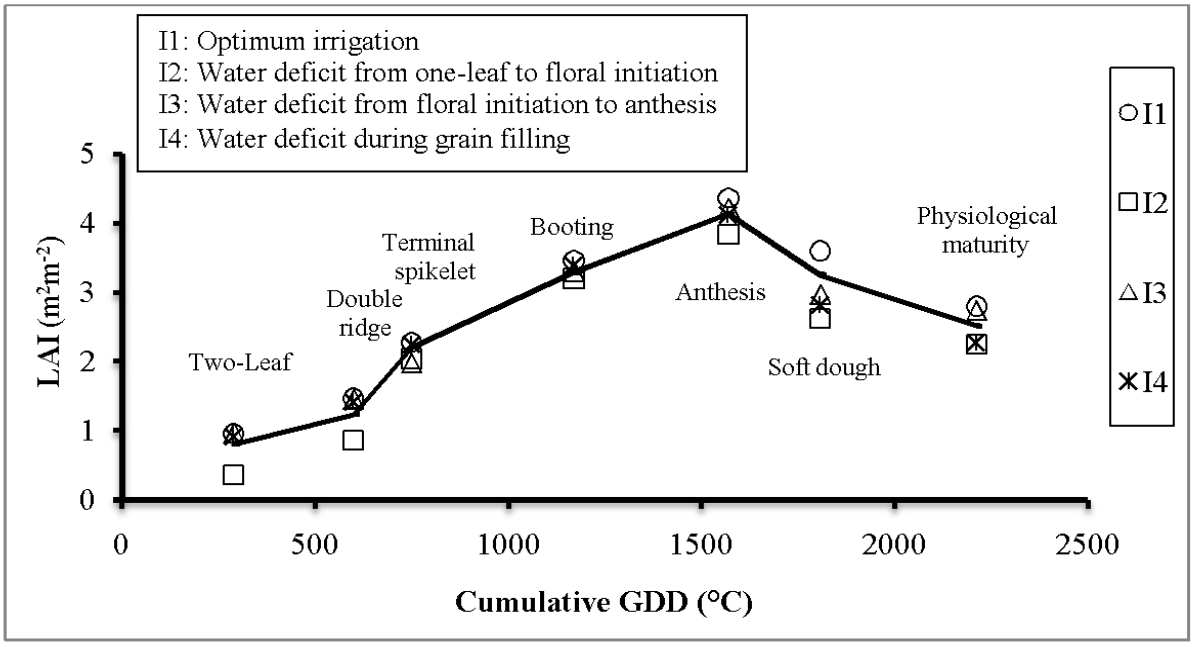

Fig. 4.3. Trend in the leaf area index (LAI) of durum wheat genotypes at different growth and developmental stages under irrigation regimes

As shown in Fig. 4.3, the curve for the leaf area index (mean) according to the cumulative growth degree-days (GDD) across the growth and developmental cycles showed an incremental and gradual trend from early growth to anthesis under optimum and water deficits conditions. The LAI incremental trend accelerated during the double ridge to terminal spikelets stage, which could be due to re-irrigation at the double ridge. Re- irrigation after water deficit (one-leaf to double ridge) increased the LAI from 0.861 to 2.035. However, it was still lower than the I1 and I4 irrigation treatments. With progressing growth, after anthesis the LAI decreased until physiological maturity. However, the highest (4.35) and lowest (3.82) leaf area index at anthesis belonged to the plants under optimum irrigation and I2 water deficit treatments respectively (Table 4.2 and Fig. 4.3).

4. 3.2.1.2 Comparison of Leaf Area Index in Different Genotypes

As shown in Table 4.2, there were significant differences in LAI values among the studied durum and bread wheat genotypes (G1, G2, G3, G4 and G5) at all growth and developmental stages, except at the two-leaf and terminal spikelets stages. In addition, as expected, the LAI increased during growth, from two-leaf stage to anthesis but decreased after anthesis to maturity. However, the LAI values in the different genotypes studied exhibited different values. The largest values belonged to the G2 (4.44), G3 (4.38), G1 (4.07), G5 (3.87) and G4 (43.85) genotypes at the anthesis, respectively. On the other hand, the results showed that during the two-leaf to terminal spikelets stage (early season) the G5 genotype exhibited the largest LAI compared to the other genotypes while the G2 genotype had the largest LAI before and post anthesis. It showed higher and relatively stable LAI value compared to the other genotypes at all the growth and developmental stages. Remarkably the high LAI at anthesis, double ridge and physiological maturity in the G2 durum wheat genotype were correlated with

the increase in the accumulation of dry matter during grain filling, compared to other genotypes (Tables. 4.1 and 4.2). On the other hand, the high LAI in the G5 genotype at the early season (two-leaf to terminal spikelets) did not translate to an increase in their total accumulation of dry matter at terminal maturity. This showed that to remain high in LAI during grain filling was more important than to have an early season high LAI. Chandrasekhar *et al.* (2000) and Araus *et al.* (2002; 2003), working on durum wheat, reported a close relationship between the leaf area index and final yield production. They reported that reduction of radiation interception affected by a decrease in LAI caused a significant reduction in the final yield. Other researchers have reported different LAI values that can be attributed to genotypic differences in wheat (Robertson and Giunta 1994).

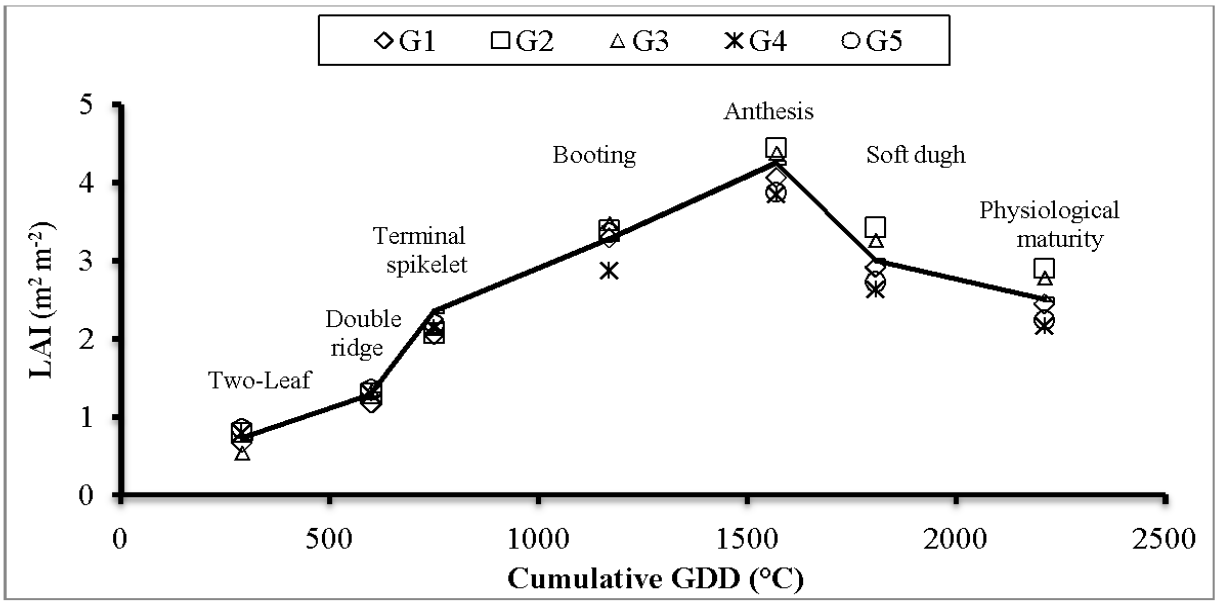

Fig. 4.4. Trend in the leaf area index at growth and developmental stages of durum wheat genotypes

The increasing pattern of the leaf area index for the different durum and bread wheat genotypes (Fig. 4.4) according to the cumulative growth degree-days during the growth and developmental cycles are similar to that shown in Fig. 4.2 for the effect of the water irrigation regimes. The largest LAI value (4.45) belonged to the G2 durum

wheat genotype at anthesis and about 1500 GDD with subsequent GDD, the LAI values decreased after anthesis to physiological maturity (Fig. 4.4).

4.3.2.2 Crop Growth Rate (CGR)

Crop growth rate (CGR) is often described as the increase in biomass of the plant on a unit of land over a unit of time. In agronomy, it is considered as an important physiological factor and criteria for assessing crop productivity, during the different growth and developmental stages. The results (Appendix 9) shows that the effect of the irrigation regime on the crop growth rate (CGR) was highly significant (p <0.01) for all growth and developmental stages. In addition, the genotypic effect on the CGR was highly significant (p <0.01) only at the double ridge and booting stages. Furthermore the interaction effect of irrigation regime and genotype on the crop growth rate was highly significant at the double ridge, soft dough and physiological maturity stages (Appendix 9).

4.3.2.2.1 Effect of Different Irrigation Regimes on Crop Growth Rate (CGR)

Water deficit treatments (I2, I3, and I4) caused different effects on the crop growth rate (CGR) compared to optimum irrigation. As expected, (Tables 4.2 and Fig. 4.3), the CGR was highest in each of the growth and developmental stages under optimum irrigation compared to the water deficit conditions. In addition, water limitation during the one-leaf to double ridge (I2) reduced the CGR more than the other irrigation regimes until anthesis. The highest reduction in CGR after anthesis was observed in the I3 and I4 water deficit treatments compared to optimum irrigation and the I1 water deficit treatment. However, the statistic difference between them was not significant. In addition, the negative effect of the early season water deficit (I2) in decreasing the CGR compared to optimum irrigation in each of the stages extended until

the physiological maturity stage and even under re-irrigation at the double ridge stage (Table 4.3).

Table 4. 3. Effect of water deficit and genotype on crop growth rate (CGR) in different growth and developmental stages of durum and bread wheat genotypes

Treatments	Crop Growth Rate (mg m^{-2} day^{-1})					
	Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
regimes Irrigation						
I1	359.3 a	631.6 a	836.1 a	1164 a	781 a	614.1 a
I2	223.1 b	366.2 c	545.5 b	779.5 b	555.7 b	352.5 b
I3	320.1 a	464.2 b	676.2 b	959.3 ab	348.2 b	257.7 b
I4	350.7 a	635.2 a	810.4 a	1135 a	418.7 b	253.5 b
LSD value	96.38	70.91	157.90	225.6	216.90	218.70
Sx	18.38	13.53	30.12	82.09	41.37	41.72
Genotypes						
G1	304.8 b	512.1 a	683.3 b	951.1 a	507.3 a	394.6 a
G2	287.4 b	519.5a	805.1 a	1014 a	530.4 a	379.7 a
G3	384.3 a	509.2 a	671.8 b	969.1 a	497.3 a	369.2 a
G4	297.4 b	501.6 a	753.2 ab	1014 a	522.8 a	358.9 a
G5	269.1 b	496.5 a	714.6 ab	977 a	571.8 a	344.8 a
LSD value	47.29	40.75	88.96	75.43	85.65	45.63
Sx	12.21	17.01	22.97	31.49	35.77	19.05

Column sharing the same letters indicates no significant differences (at $p < 0.01$)

Water limitation during the double ridge to anthesis stage (I3) decreased the CGR compared to optimum irrigation in each of the growth and developmental. However, the reduction in CGR after anthesis was more than that before anthesis. The effect of water deficit on the CGR compared to optimum irrigation showed reductions of 11%, 27%, 19%, 18%, 55% and 58% at the double ridge, terminal spikelet, booting, anthesis, soft dough and physiological maturity stages respectively (Table 4.3).

With regard to the importance of anthesis in plants, it is said that physiologically, when the leaf area reaches its optimum leaf area index (OLAI), crop growth rate (CGR) increases to its maximum value which was observed in this experiment (Figs. 4.3 and 4.5). The highest CGR were measured at the anthesis phase under all the irrigation regimes, although, it was lower under water deficit conditions compared to optimum irrigation. The reduction in LAI and CGR after anthesis (Figs. 4.3 and 4.5) was caused by the stunted growth at this stage which concurred with the findings of Ghodsi (2004) and Nazeri (2005). In addition, the higher accumulation of dry matter under optimum irrigation treatment compared to water deficit conditions (Fig. 4.1) concurs with the superior leaf area index and crop growth rate under similar irrigated conditions (Fig. 4.5).

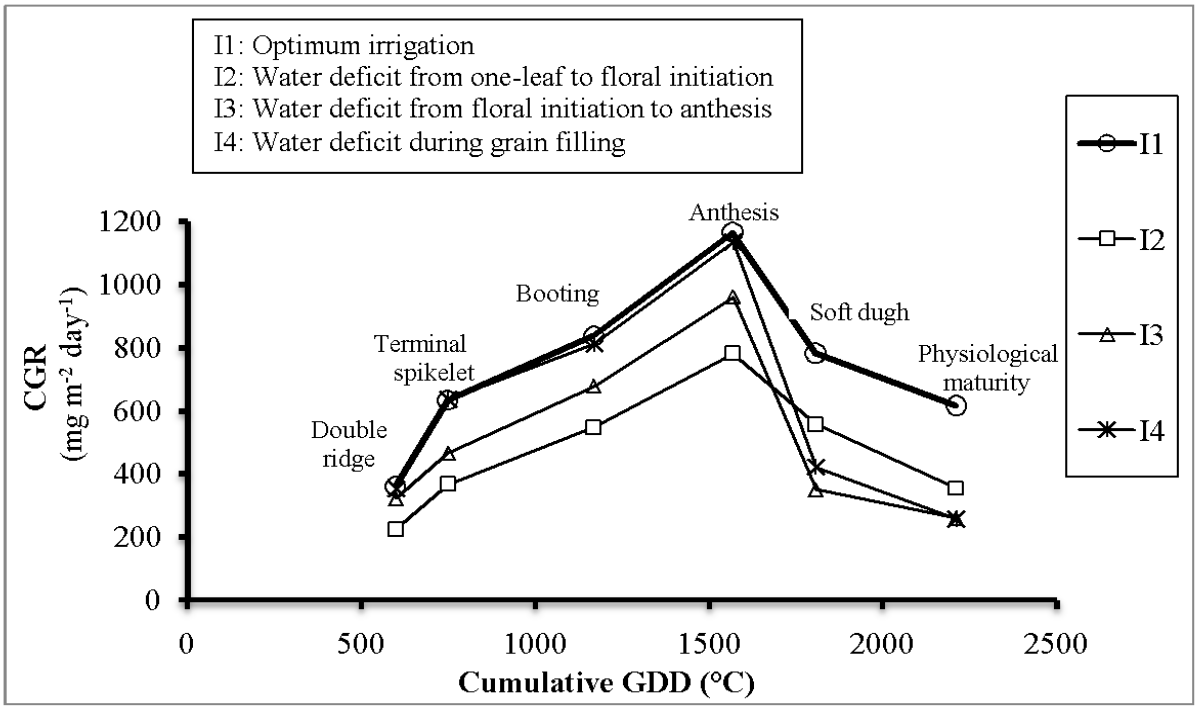

Fig. 4.5. Trend in the crop growth rate (CGR) at growth and developmental stages under different irrigation regimes

As shown in Fig. 4.5, the curve of crop growth rate according to the cumulative GDD across the growth and developmental cycles showed an incremental and gradual trend from early growth to anthesis under optimum and water deficit conditions, which was similar with the LAI trend shown earlier. However, as the growth and developmental stages progresses, the slope of the CGR curve from the anthesis to soft dough exhibited severe decline under I3 and I4 treatments compared to the I1 and I2 treatments. The negative effect of water stress at the anthesis period compared to early season (I2) may low cause those changes in the values of crop growth rate.

4.3.2.2.2 Comparison of Crop Growth Rate in the Different Genotypes

As shown in Appendix 9, there were significant differences in CGR between the durum and bread wheat genotypes at the double ridge and booting stages. Richards *et al.* (2002) reported that the early season CGR under water deficit conditions, was very important for the establishment of the young plants and consequently to overcome the soil surface evaporation. In this study, the bread wheat genotype (G3) showed a significant difference in CGR (higher) compared to other genotypes in the early season (double ridge) stage. It had also shown higher cumulative dry matter at a similar stage until anthesis (Table 4.1). In addition, with progressing growth stages, from the double ridge stage to anthesis, the CGR increased in all the genotypes studied, but it decreased subsequently from anthesis to maturity. However, there were no significant differences between the genotypes at these stages. The highest values of the CGR belonged to the G2 (1014 mg m^{-2} day^{-1}), G4 (1014), G5 (977), G3 (969) and G1 (951) genotypes respectively at anthesis. The lowest crop growth rate was observed in the G5 genotype at the double ridge growth stage.

4.3.2.3 Relative Growth Rate (RGR)

The relative growth rate (RGR) indicates the dry weight increase in plant over a time interval in relation to the initial weight. It is usually used as a parameter to compute the crop growth over time. The analysis of variance as shown in Appendix 10 revealed that the effect of the irrigation regimes on the relative growth rate was significant (p <0.05) at the terminal spikelet and booting stages while the genotypes exhibited highly significant (p <0.01) effects on this growth index at the double ridge and booting stages, similar to that observed for CGR above. In addition to this the interaction effect of irrigation regime and genotype was significant on the relative growth rate at the terminal spikelet stage (Appendix 10).

4.3.2.3.1 Effect of Different Irrigation Regimes on Relative Growth Rate (RGR)

According to Moles and Westoby (2004), water deficit is the main limiting factor for relative growth rate in semi-arid conditions, where it strongly limits both growth and seedling survival through terminal growth. As shown in Table 4.4 and Fig. 4.6, the relative growth rate (RGR) showed a decreasing trend during the early to terminal growth stages under different water irrigation regimes (I1, I2, I3, and I4). However water limitation at all stages (I2, I3, and I4) brought about a high reduction in the RGR values compared to the control (optimum irrigation, I1). All the growth parameters, namely, RGR, CGR, LAI and CDM recorded lower values under water deficit conditions compared to optimum irrigation throughout all the developmental stages (Figs. 4.1, 4.3, 4.5, and 4.6).

Table 4.4 Effect of irrigation regime and genotype on relative growth rate (RGR) in different growth and developmental stages of durum and bread wheat genotypes

	Relative Growth Rate (mg g^{-1} d^{-1})					
Treatment	Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
Irrigation regime						
I1	2.39 a	2.22a	1.90 a	1.35 a	0.84a	0.43a
I2	1.79 b	1.76c	1.53 b	1.30 a	0.72ab	0.38ab
I3	2.29 a	1.8bc	1.59 b	1.27 a	0.42b	0.23bc
I4	2.27 a	2.11ab	1.60 b	1.34 a	0.41b	0.19c
LSD value	0.36	0.27	0.19	0.17	0.41	0.16
Sx	0.13	0.08	0.05	0.06	0.14	0.06
Genotype						
G1	2.22 ab	1.99 a	1.66 ab	1.29 a	0.589 a	0.38 a
G2	2.07 b	2.14 a	1.77 a	1.36 a	0.578 a	0.27a
G3	2.42 a	1.81ab	1.498b	1.31 a	0.54 a	0.30 a
G4	2.14 b	1.98 a	1.76 a	1.32 a	0.59 a	0.31 a
G5	2.08 b	2.11 a	1.75 a	1.35 a	0.66 a	0.29 a
LSD value	0.24	0.19	0.18	0.08	0.12	0.54
Sx	0.63	0.08	0.04	0.03	0.05	0.22

Column sharing the same letters indicates no significant differences (at $p < 0.01$)

The biggest reduction in RGR during early growth to anthesis was observed in plants under the I2 water deficit treatment, while the lowest values after anthesis were seen in the I3 and I4 treatments where the RGR decreased from anthesis to the terminal maturity in all the different irrigation regimes with the highest reduction observed in the I3 and I4 treatments during grain filling. The negative effects of water deficit on the relative growth rate at the reproductive (I3) and grain filling (I4) phases were more than vegetative stage (Table 4.4) which concurred with the results obtained for LAI, CGR and total dry matter at those stages (Tables 4.1, 4.2, 4.3 and 4.4).

Simane (1993) suggested that amongst the growth parameters, the relative growth rate is an important calculable and dependable index, which clearly show differences in grain yield under water deficit conditions. They reported that both CGR and RGR values were reduced under severe water deficit conditions in comparison to optimum or low moisture deficit of wheat. A similar observation was recorded in the present study. This suggests that the reduction in CGR and accumulation of dry matter under water deficit conditions could be the result of a reduction in the RGR.

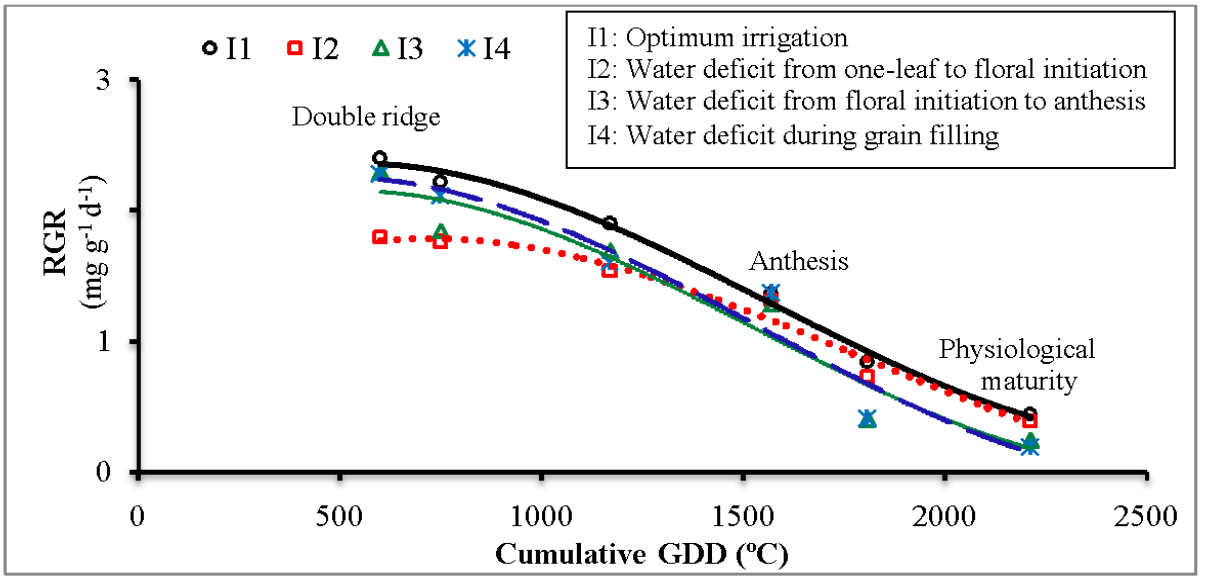

Fig. 4.6. Trend in the relative growth rate (RGR) at growth and developmental stages under different irrigation regimes

4.3.2.3.2 Relative Growth Rate (RGR) in Different Genotypes

A comparison of RGR amongst the different genotypes showed significant differences at the double ridge and booting stages, which were similar with the CGR trend (Tables 4.3 and 4.4). However there were no significant differences among the RGR values in other growth and developmental phase. The highest RGR value was seen at the double ridge stage, exhibited by the G3 genotype while at booting it belonged to the G2, G4 and G5 genotypes respectively. The trend of the RGR curve was similar to that shown with the studies on the effects of the irrigation regimes.

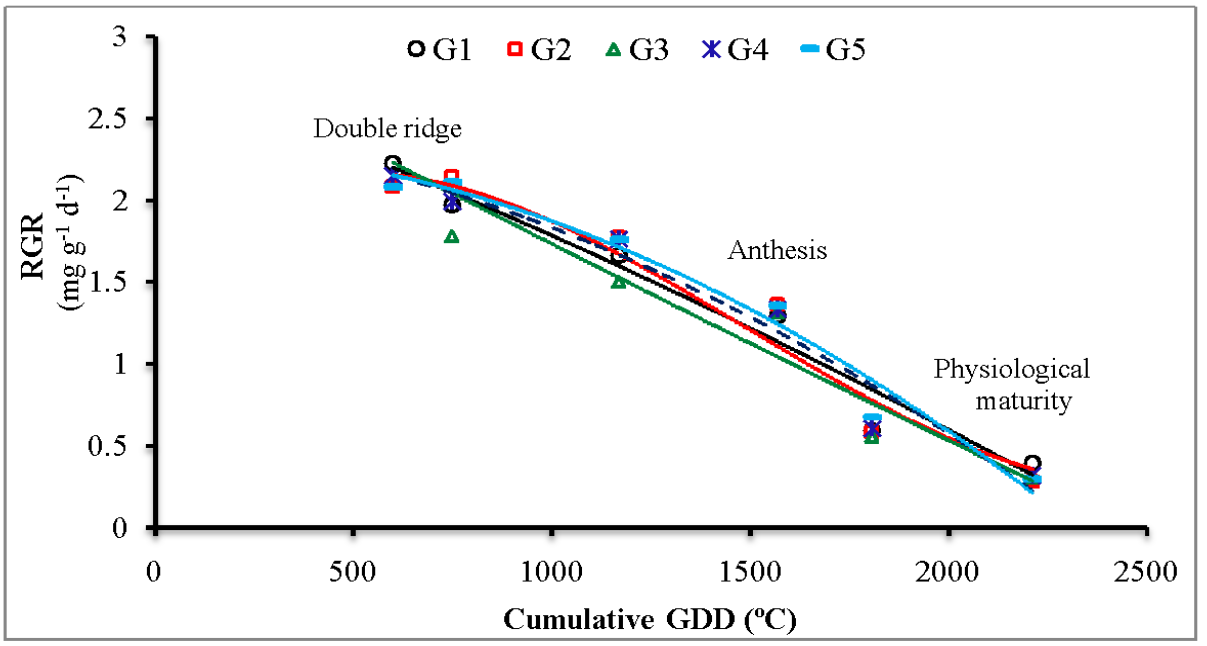

Fig. 4.7. Trend in the of the relative growth rate (RGR) at growth and developmental stages of different genotypes

As shown in Fig. 4.7, the relative growth rate exhibited a decreasing trend through early to terminal growth stages for all the studied genotypes. However, there were slight differences in RGR values at certain growth and developmental stages. The highest RGR values belonged to the G3 genotype (2.42 mg g^{-1} d^{-1}), followed by genotypes G2 (2.14 mg g^{-1} d^{-1}), G2 (1.77 mg g^{-1} d^{-1}), G2 (1.35 mg g^{-1} d^{-1}), G5 (0.67 mg g^{-1} d^{-1}) and G1 (0.38 mg g^{-1} d^{-1}) at double ridge, terminal spikelets, booting, anthesis, soft dough and physiological maturity stages, respectively. From this, it can be concluded that the G3 and G2 genotypes exhibited the highest values for RGR and this is in tandem with the increase in the cumulative dry matter (Table 4.1 and Fig. 4.2). These results are in agreement with the findings of Ghodsi (2004) in bread wheat and Simane *et al.* (1993) in durum wheat. Differences in RGR amongst the different genotypes studied under water deficit conditions were noted throughout the growth and developmental phases.

4.3.2.4 Net Assimilation Rate (NAR)

According to Van der Werf (1998) and Gardner *et al.* (2003), the net assimilation rate (NAR) is the net gain of assimilates by the plant per unit leaf area and time, which can vary with the age and physiological health of the plants. It can therefore provide a limited estimation of photosynthetic efficiency by measuring how well a plant uses available leaf area to produce biomass. As shown in Appendix 10, the effect of water irrigation regimes on NAR parameter was highly significant (p <0.01) at the terminal spikelet, booting, soft dough stages and significant (p <0.05) at the double ridge, anthesis and physiological maturity stages. Furthermore, the genotypic effects on NAR were highly significant at the double ridge, booting, anthesis and soft dough stages, while the interaction effect of the irrigation regime and genotype was highly significant at the booting stage and significant at the anthesis to physiological maturity phases (Appendix 11).

4.3.2.4.1 Effect of Different Irrigation Regimes on Net Assimilation Rate (NAR)

Table 4.5 shows mean values of net assimilation rate (NAR) at different growth and developmental stages under optimum irrigation and water deficit conditions. The trend in NAR was similar to that observed for RGR above. Similarly, it exhibited a general decreasing trend from the early to the terminal growth stages under the different water irrigation regimes (I1, I2, I3, and I4). However, the slope of NAR curve was affected in response to the severity of water deficit and stages of the growth. Water deficit at the all the growth stages (I2, I3, and I4) caused a decline in the NAR values when compared to optimum irrigation (I1). Generally, this study has shown that water limitation caused a negative effect on growth parameters values (LAI, CGR, RGR, NAR) and also cumulative dry matter compared to optimum irrigation throughout the growth and developmental phases (Figs. 4.1, 4.3, 4.4, 4.6, and 4.8). A significant and

positive correlation between RGR and NAR was reported by Loveys *et al.* (2002) and Poorter and Nagel (2000). The results of the present study concurred with these previous findings on durum and bread wheat genotypes.

As shown in Table 4.5, the biggest reduction in NAR during the early growth stage to anthesis phase was found under the I2 water deficit treatment while the lowest NAR values after anthesis were made under I3 (150 and 110 mg m^{-2} d^{-1}) and I4 (145 and 101 mg m^{-2} d^{-1}) treatments. Similarly, the RGR decreased at the same growth phases (Table 4.4 and Fig. 4.6). It seems, a severe decline in NAR during the reproductive and grain filling phases, compared to the vegetative phase, is due to the reduction in LAI and CGR at the post-anthesis stage which consequently caused a severe reduction in the RGR and total dry matter at the same phase (Tables 4.1, 4.2, 4.3, 4.4 and 4.5). With the application of water deficit treatment at the I3 (double ridge to anthesis) and I4 (anthesis to late grain filling), NAR values decreased during anthesis to physiological maturity compared to optimum irrigation. Hence there were significant differences in NAR between optimum irrigation and the water deficit conditions (I2, I3, and I4).

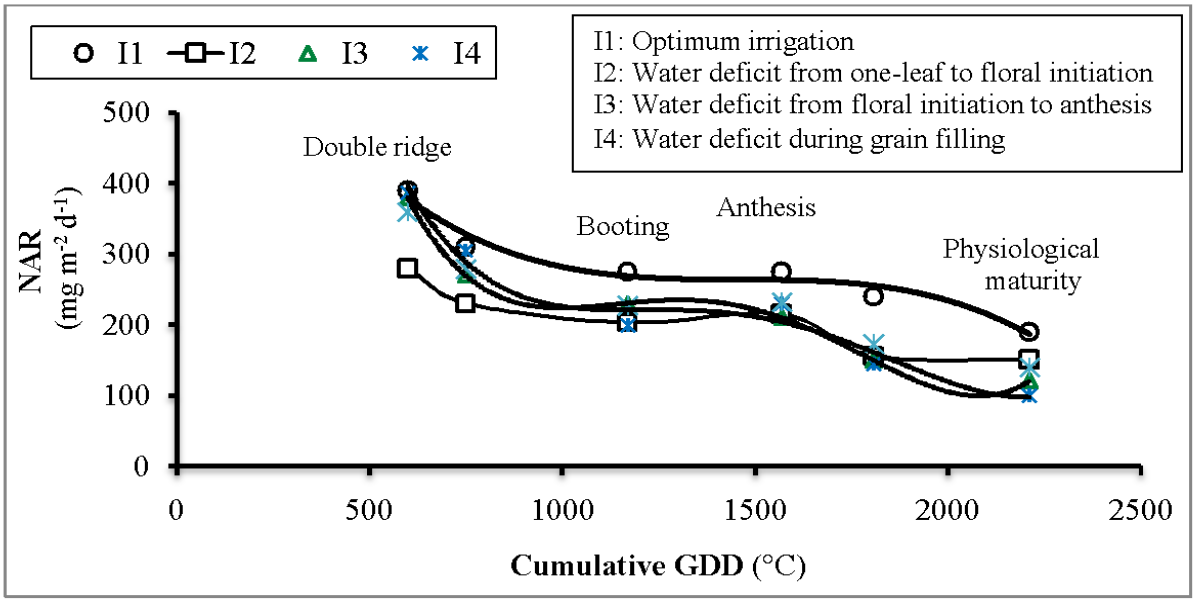

Fig. 4.8. Trend in the net assimilation rate (NAR) at growth and developmental stages under different irrigation regimes

As is the common pattern (Figs. 4.6 and 4.8), all the irrigation regimes caused a reduction in RGR and NAR with ageing, although the cumulative dry matter increased (Fig. 4.1). Apart from these general trends, NAR tended to increase from booting to anthesis, which could be an incremental response in LAI at the growth peak (1570 GDD) at the anthesis phase. On the other hand, the decrease in LAI between anthesis and grain filling also caused a decrease in NAR at those growth phases (Figs. 4.3 and 4. 8).

Table 4.5 Effect of water deficit and genotype on net assimilation rate (NAR) in different growth and developmental stages

Treatments	Net Assimilation Rate (mg m^{-2} d^{-1})					
	Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
Irrigation regime						
I1	390 a	310 a	275 a	275 a	240a	190a
I2	290 b	230 b	203 b	185 b	155b	118ab
I3	380 a	270 ab	230 b	210 b	150b	110b
I4	387 a	305 a	273 a	230 ab	145b	101b
LSD value	84.94	47.25	42.50	56.11	79.39	70.22
Sx	30.91	9.01	8.11	20.42	18.96	14.35
Genotype						
G1	339 b	298 a	224 bc	232.8 bc	206.5 b	176.3 a
G2	344 b	315 a	256 ab	229.8 bc	207.7 b	153.1ab
G3	399 a	310 a	215c	220.4 c	197.8 b	153.8 ab
G4	335 b	287 a	260 a	258.8 a	229.6 ab	172.6 a
G5	320 b	285 a	226 bc	246.2 ab	231a	167.8 ab
LSD value	57.00	32.79	29.47	27.79	34.85	23.98
Sx	18.07	13.69	7.610	9.648	12.10	10.01

Column sharing the same letters indicates no significant differences (at p <0.01)

4.3.2.4.2 Net Assimilation Rate (NAR) in Different Genotypes

As shown in Table 4.5 and Fig. 4.9, most of the studied genotypes showed their highest RGR and NAR at the early stages of development and thereafter the values reduced with increasing plant age and cumulative degree-days. These variations in RGR were mainly explained by the changes in NAR, as there is a strong correlation between both parameters, as shown in the finding of Poorter and Nagel (2000) in wheat. Earlier, Pandey *et al*. (1978) suggested that the reduction in NAR at the terminal stages could be due to the interaction effect of leaf shading and increase in the number of older leaves, which would reduce photosynthetic ability.

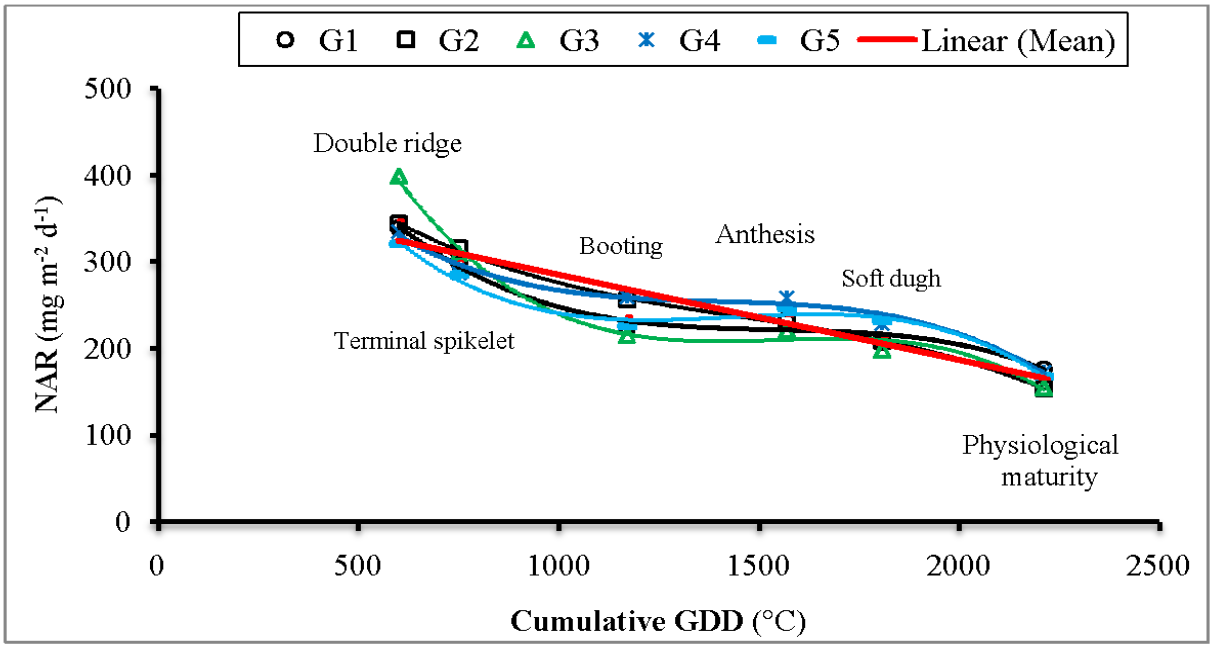

Fig. 4.9. The relationship between net assimilation rate and cumulative growth degree-days in different genotypes

In addition, there were significant differences amongst durum and bread wheat genotypes and the different growth phases. The highest NAR values, depending on the growth stages, were observed in the G3 (double ridge), G2 (terminal spikelet and booting), G4 (anthesis), G5 (soft dough) and G1 (physiological maturity) genotypes. A comparison of the RGR and NAR values due to genotypic effects indicated that the

highest values for both growth parameters were found in similar genotypes, which concurred with the results of Galme´s *et al.* (2005) and Loveys *et al.* (2002. In conclusion, the results of the present study showed that the influence of NAR on the RGR strongly depend on the genotypic effects in different stage of the growth. This probably reflects the differences in response and adaptation to environmental conditions shown by the different genotypes.

4.3.3 Photosynthesis Active Radiation Interception (PARI)

Photosynthesis active radiation interception (PARI) is a function of the green leaf area index and radiation extinction coefficient. The effects of the irrigation regimes, genotype and their interaction effects on PARI, as shown in Appendix 12, were highly significant (p <0.01) from the early to the late growth and developmental phases, although the radiation extinction coefficient was not affected by these effects. The present results concurred with the findings of Robertson and Giunta (1994) and Fisher (2001) who have shown a significant difference in PARI due to LAI at the different growth and developmental in wheat. Nazeri (2005) reported a similar relationship between different genotypes and PARI in triticale, which is in agreement with the current results (Appendix 12).

4.3.3.1 Drought-Induced Changes on Photosynthesis Active Radiation Interception (PARI)

The percentage PARI values under the different irrigation regimes throughout the growth and developmental phases of the durum and bread wheat genotypes are summarized in Table 4.6. The values obtained show a similar trend with those shown for LAI (Table 4.2). With increasing cumulative GDD, from early growth stage to anthesis, the plant canopy PARI values increased gradually under all the irrigation regimes. Thereafter, it reduced remarkably until the grain filling stage. The intercepted

PAR exhibited higher values for plants under optimum irrigation compared to those under water deficit conditions. It also appears that an increase in LAI values contributed to the increase in the PARI percentage (Tables 4.2 and 4.6).

Among the water deficit treatments, water limitation at the early growth stage (I2) and grain filling (I4) stage reduced the PARI percentage in comparison to the other irrigation regimes. The negative effect of the early season water deficit (I2) in decreasing the PARI extended until the anthesis phase. The results showed that the effect of early water deficit in decreasing LAI also reduced PARI in the I2 water deficit treatment. Robertson and Giunta (1994) reported similar results in wheat and barley. The highest and lowest PARI values were found at anthesis and double ridge phases, respectively. These values coincided with the lowest LAI value at the early growth stage and the peak at the anthesis ((Tables 4.2 and 4.6).

Up to the double ridge stage both the I1 (optimum irrigation) and I3 (water deficit from double ridge to anthesis) treated plants have a similar irrigation regime and as expected there was no significant difference between them with regard to PARI values at that stage (Table 4.6). However, the difference in PARI between I1 and I3 irrigation treatments increased after the double ridge stage, where it was 2%, 7%, 13%, 10% and 12% at the terminal spikelet, booting, anthesis, soft dough and maturity stages respectively. Re-irrigation at the anthesis could not compensate for the reduction in leaf area and consequently the PARI values. The importance of intercepted photosynthetic active radiation and its effect on the vegetative and reproductive phases have been reported by Reynolds *et al.* (2000) and Fischer (2001).

Table 4. 6 Effect of different irrigation regimes and genotypes on photosynthesis active radiation interception (PARI) and radiation extinction coefficient (k) at double ridge, terminal spiklets (TS), booting, anthesis, soft dough and physiological maturity (PM) phases

Treatments	Photosynthesis Active Radiation Interception (%)						
	Double ridge	TS	Booting	Anthesis	soft dough	PM	k
Irrigation regimes							
I1	36.69a	46.69a	57.19a	86.01a	82.93a	74.71a	0.48a
I2	33.40b	42.40b	48.90b	69.60b	68.60b	70.67a	0.47a
I3	36.32a	44.32ab	50.82b	73.20b	72.33b	62.04b	0.47a
I4	35.59a	45.59a	56.09a	84.53a	64.40c	58.05b	0.47a
LSD	2.69	2.69	2.67	5.43	4.16	8.14	0.01
Sx	0.51	0.51	0.51	1.03	0.79	1.55	0.01
Genotype							
G1	35.88 a	46.88 a	54.38 a	75.7a	74.17 a	71.1 a	0.44a
G2	30.75 b	40.75 b	54.22 a	79.2a	75.92 a	73.6 a	0.49a
G3	31.52 b	41.52 b	54.38 a	78.1 a	77.25 a	72.6 a	0.47a
G4	35.72 a	46.72 a	54.20 a	77.3 a	73.08 b	67.3 b	0.45a
G5	32.38 b	42.38 b	48.88 b	71.7b	71.67 b	63.4 c	0.47a
LSD	2.59	2.59	5.19	5.51	3.15	4.50	0.01
Sx	0.67	0.67	0.67	1.42	1.09	1.16	0.002

Column sharing the same letters indicates no significant differences (at $p < 0.01$)

Table 4.6 also shows no significant difference for PARI values between the I1 (optimum irrigation) and I4 (water deficit during grain filling) treatments. This is probably due to fact that both treatments shared similar irrigation periods until anthesis. However, the application of water deficit from anthesis onwards until late grain filing (I4) reduced PARI at the soft dough and physiological maturity stages compared to optimum irrigation and the other water deficit conditions. The photosynthetically active radiation interceotion reduced by 17%, 13% and 23% under I2, I3 and I4 water deficit treatments compared to optimum irrigation..

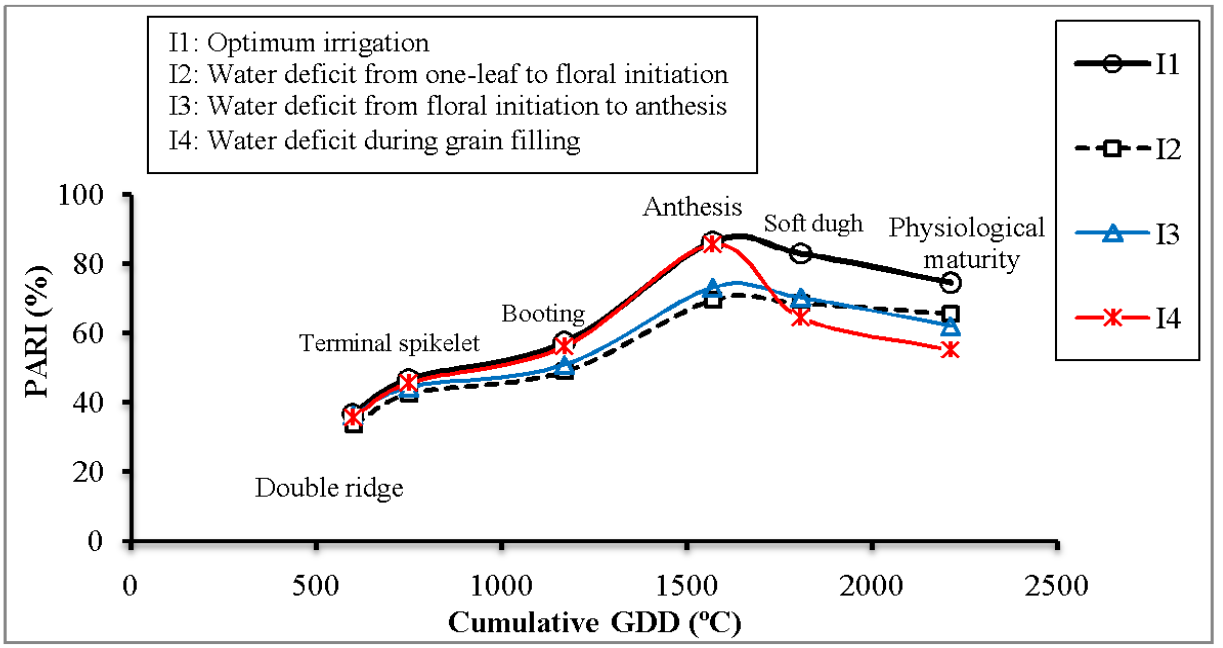

Fig. 4.10. Effect of different irrigation regimes on trend of photosynthetic active radiation interception (PARI) at growth and developmental stages

In addition, the PARI values at physiological maturity exhibited only a small change. Hence, the reduction of the photosynthesis active radiation interception at physiological maturity was 6%, 18% and 23% in the I2, I3 and I4 treatments, respectively, compared to optimum condition (I1). The decrease in PARI during grain filling period was affected by early leaf senescence photosynthesis active radiation interception and finally crop growth rate under I4 water limitation treatment (Figs. 4.3, 4.4, 4.10 and 4.11).

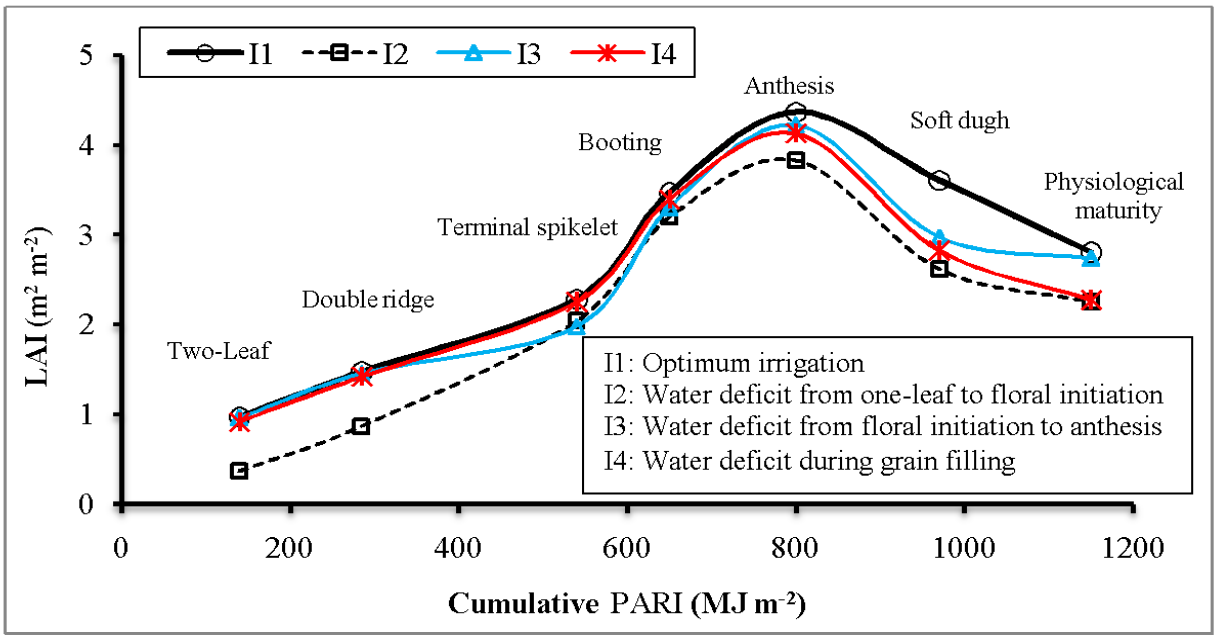

Fig. 4.11. Effect of different irrigation regimes on trend of gran leaf area index (LAI) at growth and developmental stages

The effect of water deficit during the grain filling stage caused leaf rolling and reduction in the effective leaf area.Thereafter, terminal water deficit resulted in rapid leaf senescence and defoliation in the plants. Consequently, it caused a significant reduction in the LAI and PARI values. Araus *et al.* (2003), Chandrasekhar *et al.* (2000) and Nazeri (2005) have reported similar observations on bread wheat, durum wheat and triticale, respectively.

4.3.3.2 Photosynthesis Active Radiation Interception (PARI) In Different Genotypes during Growth and Developmental Phases

As shown in Table 4.6, there were significant differences between the studied genotypes with regard to PARI values at the different growth and developmental phases. The PARI readings showed an incremental trend for all the genotypes from the double ridge to anthesis stage, but thereafter it decreased until grain filing. The average PARI readings for the different genotypes were 33%, 43 %, 53%, 76%, 74% and 69% at the double ridge, terminal spikelets, booting, anthesis, soft dough and physiological

maturity stages, respectively. Amongst genotypes, G1 and G4 exhibited the highest PARI values at the double ridge (35%) and terminal spikelets (46%) stages, while at the booting stage, apart from genotype G5 which had the lowest reading, all the other genotypes did not show any significant difference in PARI. As shown in Fig. 4.12, with decreasing PARI, during grain filling, the earlier dominant trend shown by genotypes G1 and G4 had changed. From anthesis to grain filling, the results showed that the G2 and G3 genotypes exhibited the highest values for PARI compared to the other genotypes. The lower reduction in the radiation interception as shown by genotypes G2 and G3 during grain filling can be related to similar observations seen with the LAI readings (Figs 4.4 and 4.12). Genotypic differences due to leaf area index and photosynthesis active radiation interception have been reported previously in different cereals crops (Robertson and Giunta 1994; Legg *et al.* 1979) which were similar to the results of the present study.

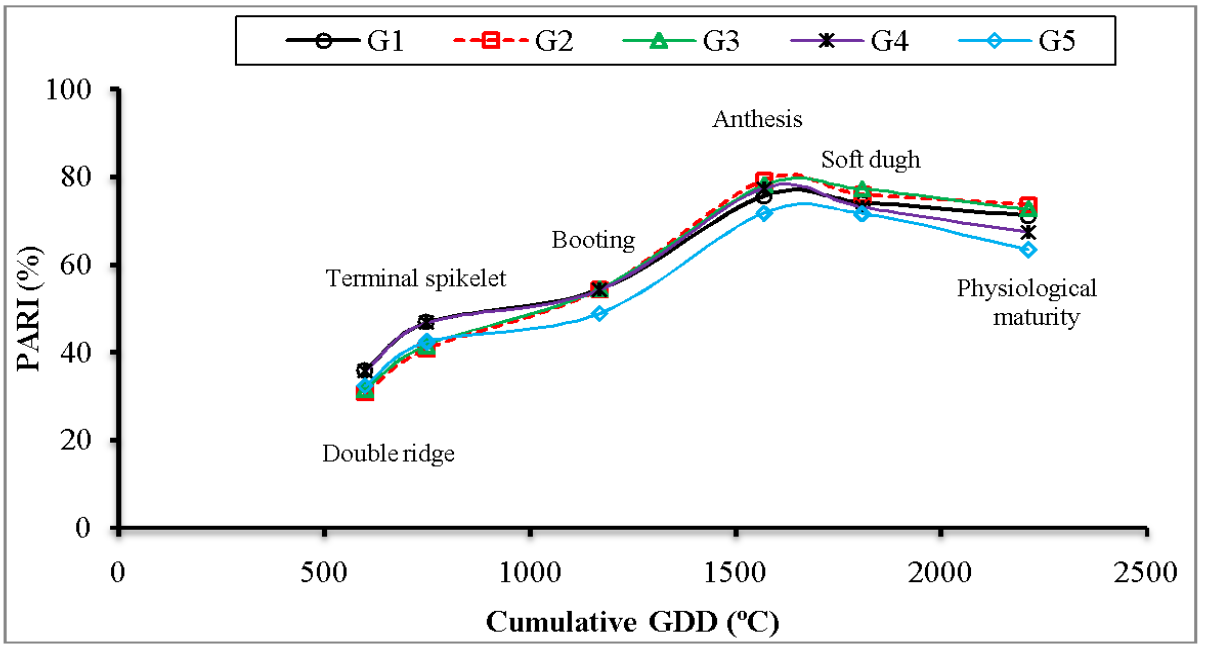

Fig. 4.12. Trend in photosynthesis active radiation interception at growth and developmental stages of different genotypes

4.3.4 Radiation Use Efficiency (RUE)

The relationship between plant dry matter and radiation intercepted has been termed as the radiation use efficiency. In the other words, it can be defined as the ratio of dry matter produced per unit of radiant energy used in its production (Monteith 1977).

4.3.4.1 Effect of Different Irrigation Regimes on Radiation Use Efficiency (RUE)

As shown in Fig. 4.13, there was an incremental trend for radiation use efficiency following the growth and developmental phases. The increasing RUE is affected by the extension of the leaf area (LAI) which consequently increased the photosynthetic active area for intercepting greater incoming radiation. The trend in RUE was similar to that shown for LAI and cumulative dry matter (Figs 4.1 and 4.3). No significant differences in RUE amongst the plants in the different irrigation regimes were observed. Although the I1 and I4 treatments showed some differences they were comparable to the I2 and I3 water deficit conditions (Fig. 4.13).

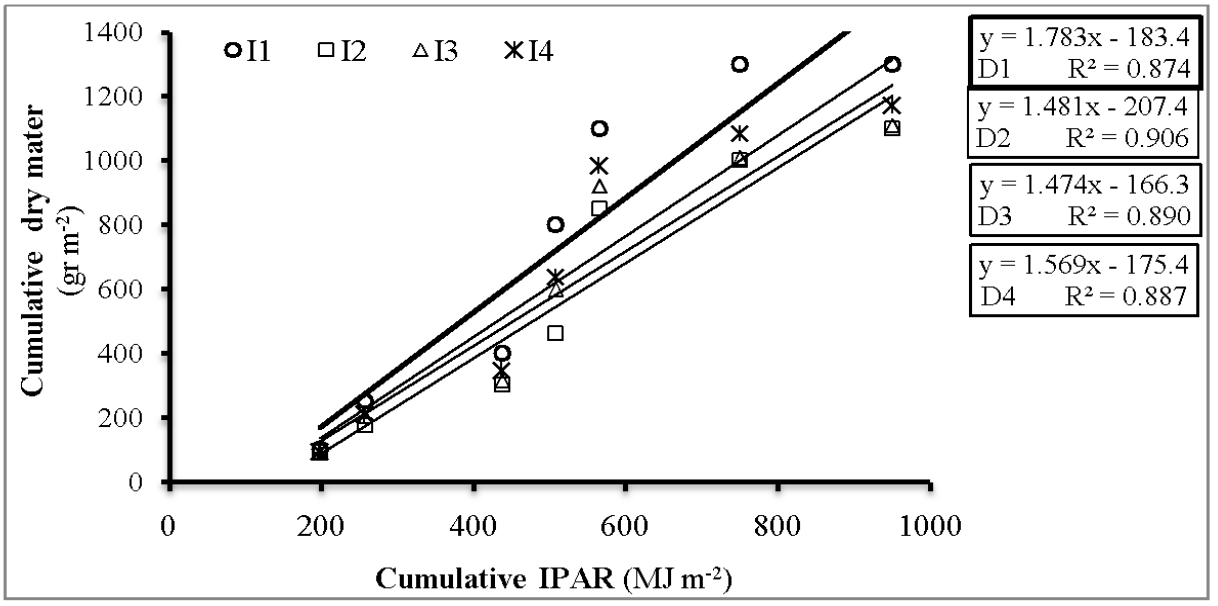

Fig. 4.13. Relationship between cumulative photosynthetic active radiation interception and cumulative dry matter under different irrigation regimes

Generally, it appears that the decreasing leaf area index and intercepted radiation by the plant canopy under water deficit caused the change in the RUE and dry matter. Several studies have reported the linear relationship between dry matter and intercepted radiation accumulation and they are confirmed by the results of present study, which are shown in Fig. 4.13 (Monteith 1977; Sinclair and Muchow 1999; Araus *et al.* 2003). A similar decrease in the intercepted photosynthetic active radiation and cumulative dry matter under water deficit conditions caused no significant difference on the effect of water deficit treatments on radiation use efficiency. In the other words, the simultaneous reduction in the accumulative PARI and accumulative dry matter had stabilized the RUE under water deficit conditions which concurred with the findings of Ple´net *et al.* (2000); Kemanian *et al.* (2004); Nazeri (2005).

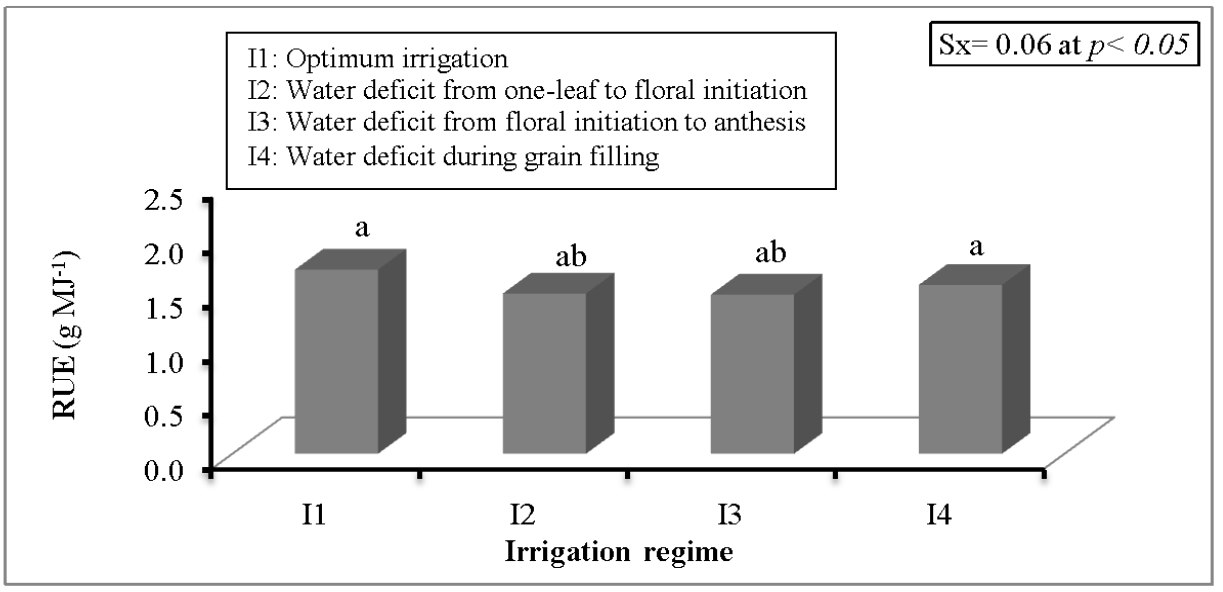

Fig. 4. 14. Effect of different irrigation regimes on radiation use efficiency (RUE) in durum wheat genotypes

As shown in Fig. 4.14, there were no significant differences among iriigation treatments due to RUE. Howevere, the results of present study showed higher values of the RUE under I1 and I4 compared to I2 and I3 treatments. It seems that the reduction in the intercepted radiation by the plant canopy (Fig. 4.9) and the reduction in dry matter

accumulation (Fig. 4.1) under water deficit conditions is a self-regulating mechanism, which decreased green leaf area, and LAI under moisture stress compared to optimum irrigation (Fig. 4.11). These results are agreement with finding of Richards (1996) which noted that the prevention of the extra radiation intercepted under water stress condition is a very important factor to overcome greater photosynthesis. It has been suggested that some drought tolerance responses, such as leaf rolling and villosity, which avoid the interception of extra radiation are self-regulating mechanisms in crops. Therefore, the decrease in LAI, PARI and consequently accumulation dry matter under water deficit conditions caused no significant difference in RUE (Figs. 4.10, 4.11 and 4.14).

4.3.4.2 Radiation Use Efficiency (RUE) in Different Studied Genotypes

There was a linear relationship for RUE between accumulative dry matter and accumulative photosynthetic active interception in the different durum and bread wheat genotypes (Fig. 4.15). As shown in Fig. 4.16, the different genotypes did not show significant differences for radiation use efficiency, although the higher values were belonged to G3 (1.64 g MJ^{-1}) and G2 (1.62 g MJ^{-1}) compared to G4 (1.62 g MJ^{-1}), G1 (1.58 g MJ^{-1}) and G5 (1.48 g MJ^{-1}) genotypes.

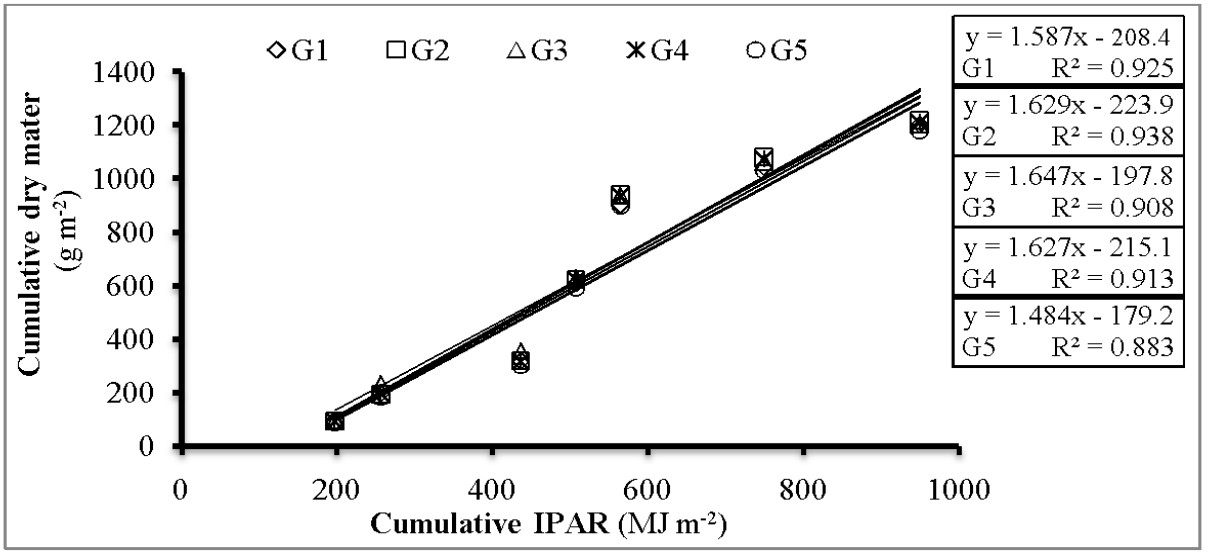

Fig. 4.15. Relationship between cumulative photosynthetic active radiation interception and cumulative dry matter in different studied genotypes

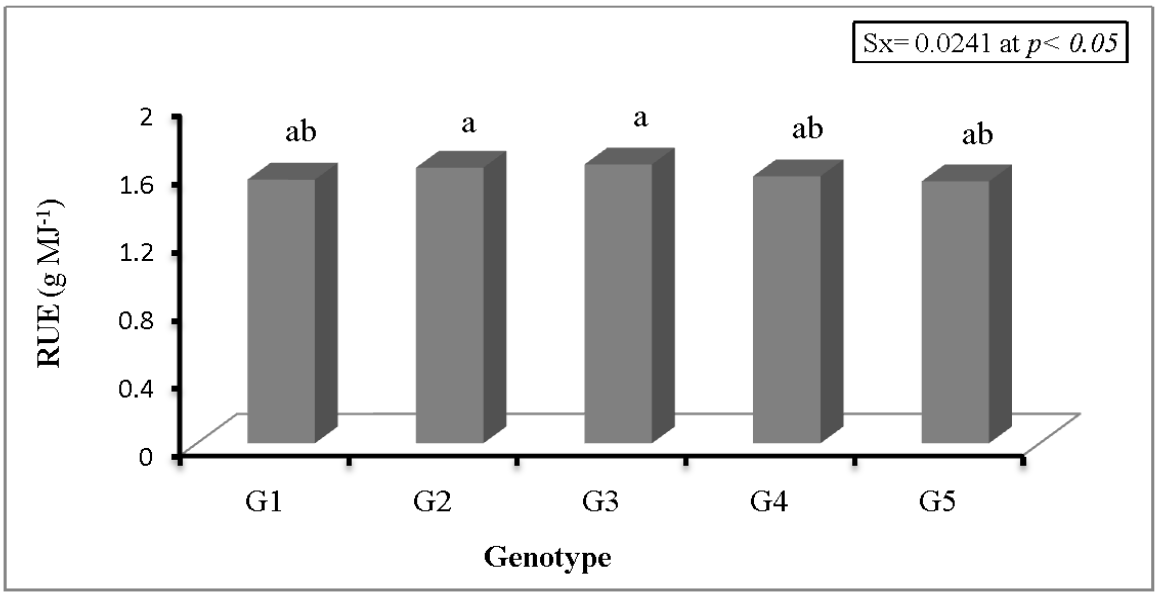

Fig. 4.16. Radiation use efficiency in different durum wheat genotypes

Comparison of the linear slopes between the different irrigations and genotypes for RUE (Figs. 4.13 and 4.15) revealed that the impact of water deficit on radiation use efficiency was more than that of genotypic effect. In addition, with increasing growth and developmental stages, the linear slope for water deficit treatments decreased compared to the optimum irrigation while there were no differences amongst the genotypes with regard to RUE with the increasing growth stages.

The results of the present study, on the RUE in the different durum and bread wheat genotypes concurred with the findings of Calderini *et al*. (1997), O'Connell *et al*. (2002) and Nazeri (2005). Their results also showed low differences for RUE in different cereals crops, while Muurinen and Peltonen-Sainio (2006) reported similar RUE values for barley and wheat. Furthermore, Robertson and Giunta (1994) reported no genotypic diversity related to radiation use efficiency amongst the different barley, triticale and wheat varieties studied.

4.4 CONCLUSIONS

Water deficit reduced LAI, CGR, RGR, NAR, PARI, RUE and accumulation of dry matter compared to optimum irrigation in the different growth and developmental stages in durum and bread wheat genotypes. However, there were no significant differences among the irrigation treatments for RUE. A significant difference in LAI and PARI under water deficit conditions reduced dry matter by 24%, 31%, 39%, 33%, 31% and 26% at the double ridge, terminal spikelets, booting, anthesis, soft dough and physiological maturity stages respectively, under I2 water deficit treatment compared to optimum irrigation in durum wheat genotypes.

The negative effect of early season water deficit (I2) on decreasing LAI and dry matter extended until terminal maturity. The rapid leaf area expansion at the early growth stage caused better plant establishment and prevented the water evaporation from the soil surface, which is known to be a very important factor to overcome the early-season drought conditions.

The reduction of CGR and accumulation of dry matter under water deficit was related to the decrease in RGR. It appear that a severe decline in NAR during the reproductive and grain filling phases was related to the high reduction in LAI and CGR at post-anthesis, which consequently caused a severe reduction in the RGR and total dry matter in the same phase. In addition, suitable condition had increased the LAI and PARI while the PARI reduced by 17%, 13% and 23% under water deficit treatments in the I2, I3 and I4, respectively. RUE stabilized under water deficit due to a simultaneous reduction in PARI and dry matter. A comparison of the linear slopes between irrigation treatments and genotypic effects due to RUE showed that the impact of water deficit on RUE was more than the genotypic effect. In the later periods of the growth and

developmental stages, the linear slope due to RUE in the water deficit treatments decreased but there were no striking differences amongst genotypes due to RUE.

The results also revealed that G2 durum wheat and G3 bread wheat genotypes exhibited the highest values for PARI from anthesis to grain filling. It seems that the lower reduction of PARI in the G2 and G3 genotypes during grain filling is related to a similar trend in LAI values (lower reduction) at the same period.

CHAPTER 5

IMPACT OF WATER DEFICIT ON REMOBILIZATION OF STORED PRE-ANTHESIS ASSIMILATES IN DURUM WHEAT GENOTYPES

5. 1 INTRODUCTION

Drought stress creates negative effects on crop growth and productivity through several ways, such as by decreasing its photosynthetic capabilities. However, crops can also react to water deficit using different complex mechanisms. Hence, improving grain yield under water deficit conditions has been considered as a very sound and important method in arid regions of the globe (Blum 1998; Chaves and Oliverira 2004; Zhang *et al.* 2008).

Several researchers suggested that grain structure and development in wheat depends on carbon provided from three sources, namely, photosynthetic assimilation, remobilization of pre-anthesis assimilates stored mainly in the stem and also the retransformation of assimilates stored temporarily in the stem after anthesis. In addition to this, photosynthetic assimilation as a source of carbon for grain filling depends on the light intensity reaching the leaves of the plant after anthesis. Furthermore, any stress, especially drought, can also decrease photosynthesis after anthesis (Kobata *et al.* 1992; Schnyder 1993; Blum 1998; Ehdaie and Waines 1996; Yang *et al.* 2000).

Photosynthetic assimilates can be limiting for the grain filling, even under mild drought conditions. Hence, the carbon reserves in the stem can be an important carbon source for grain filling (Gent 1994; Yang *et al.* 2000). Both grain dry matter accumulation and the canopy respiration are approximately identical sinks for the photosynthetic assimilates, and together their total demand for assimilates are greater in comparison with canopy photosynthesis during the wheat grain filling stage (Blum 1998). Therefore, internode reserves including the peduncle, penultimate, and the lower internodes, which are components of the stem in wheat, are eventually necessary for complete grain filling (Ehdaie *et al.* 2006).

Yang *et al.* (2000; 2001) and Plaut *et al.* (2004) reported that under suitable conditions sufficient carbohydrate accumulate in the stem before the grain-filling period. They also suggested that adequate carbohydrate storage may be dependent on plant traits, and can promote high yield potential at the pre-anthesis stages.

It has been reported that canopy photosynthesis rapidly decreases after the anthesis under terminal drought conditions (Johnson 1981). Furthermore, flag leaf photosynthesis cannot support both respiration and grain filling (Rawson *et al.* 1983; Blum 1998). Consequently, the contribution of current photosynthetic assimilates to grain filling decreases during drought and a considerable quantity of the stem reserved carbohydrates are needed to translocate to the grains during grain filling in wheat (Rawson *et al.* 1983; Gent 1994). Even under sufficient water, the pre-anthesis assimilate reserves in the stems and sheaths of wheat and rice contribute around 10 – 40% to the final grain weight (Gebbing and Schnyder 1999). Nevertheless, several researchers (Palta *et al.* 1994; Asseng and van Herwaarden 2003; Plaut *et al.* 2004) have reported that under water deficit conditions, the remobilization of the stem reserves to the grain will become more critical for grain yield. In addition, the stem reserve mobilization and its rate of development can be affected under water deficit conditions during grain filling. Other results have shown a small contribution of pre-anthesis assimilates to grain under favorable moisture conditions (Rawson and Evans 1971; Austin *et al.* 1977), while contribution of pre-anthesis assimilates to grain can increase under the water deficit (Austin *et al.* 1977; Aggarwal and Sinha 1984).

The remobilization of pre-anthesis assimilates to the grain was reduced under water deficit conditions in Hongwangmai but increased in Haruhikari bread wheat cultivars (Inoue *et al.* 2004), whilst Roshan and Chamran Iranian bread wheat cultivars produced the highest and lowest remobilization values, respectively (Ghodsi 2004). In other studies on durum wheat genotypes, the dry matter translocation efficiency changed from 9% in old cultivars to

20% in modern cultivars. Also, the contribution of pre- anthesis assimilates to grain yield increased by 31% in modern cultivars (Álvaroa *et al*. 2008).

The objective of this study was to investigate the contribution of pre-anthesis stored assimilates (stems) in grain filling of the studied durum and bread wheat genotypes under different irrigation regimes. In addition to this, the efficiency of dry matter translocation amongst genotypes was determined in order to screen suitable genotypes as drought tolerance.

5.2 MATERIALS AND METHODS

5.2.1. Field Experimental Setup

This experiment was laid out in field of Torogh Agricultural Research Station, Iran during the 2007-2008 growing seasons. The experimental design, main and sub plots were similar to those explained for field experimental setup in chapter 4. Four different irrigation regimes and five wheat genotypes (G1, HAI - OU - 17/ GREEN - 38; G2, RASCON- 37/ BEJAH- 7; G3, CHAMRAN; G4, RASCON- 39 / TILO- 1; G5, GARAVITO3 / RASCON37 // GREEN8) were applied as the main plots and sub-plots, respectively. With regard to experimental design (RCBD) each plot was consisted 12 rows 3 m in length and spaced 20 cm apart. The analysis of variance for all data was statistically calculated using MSTAT-C software package. In addition, comparative analyses of the means were performed by Duncan's Multiple Range Test ($p < 0.01$).

5.2.2 Measurements

5.2.2.1 Remobilization of Pre-Anthesis Assimilates

Twenty main shoots (including leaves and spikes) were randomly selected from each plot and cut at the soil surface at the anthesis and maturity stages. Different parameters describing the dry matter mobilization and remobilization within the plant as follows:

$$DMT = DMSa - DMSm$$

$$DMTE = [DMT / DMS\ a] * 100$$

$$CPAA = (DMT / GY) *100$$

where DMT is dry matter translocation (mg plant^{-1}); DMSa is dry matter shoot at anthesis ((leaf + culm+ spike); DMSm is dry matter shoot at maturity (leaf + culm + chaff+ spike, except grain); DMTE is dry matter translocation efficiency (%); CPAA is contribution of pre-anthesis assimilates to grain (%); and GY is grain yield (mg plant^{-1}). The dry matter remobilization parameters were calculated according to findings of Ghodsi (2004) and Nazeri (2005), Arduini *et al*. (2006) and Dordas (2009).

5.2.2.2 Spike Dry Weight and Spike Harvest Index in durum wheat genotypes

In order to compute spike dry weight (SPKDW) and spike harvest index (SHI), twenty plants (including leaves and spikes) were randomly selected from each plot at anthesis and the physiological maturity stages. The samples were kept in an incubator for 3 days at 80°C and shoot and spike dry weight measured separately in the laboratory. The spike harvest index was calculated according to Donalson (1996) and Robertson and Giunta (1994) as follow;

$$SHI\ \% = (SPKDW / TDMS) * 100$$

In this formula, SPKDW is spike dry weight at anthesis and TDMS is total shoot dry matter at physiological maturity.

5.3 RESULTS AND DISCUSSION

5.3.1 Remobilization of Pre-Anthesis Assimilates to Grain in Durum Wheat Genotypes

As shown in Appendix 13, the analysis of variance revealed that dry matter translocation (DMT) was significantly affected (p <0.05) under water deficit conditions. However both dry matter translocation efficiency (DMTE) and contribution of pre-anthesis assimilates to grain (CPAA) were highly significantly affected (p <0.01) by genotype and also by the interaction effect of water deficit and genotype (Appendix 13).

5.3.1.1 Effect of Water Deficit on Dry Matter Translocation of Durum Wheat Genotypes

As shown in Fig. 5.1, there was no significant difference in dry matter translocation (DMT) between the optimum irrigation treatment and the I2 and I3 water deficit treatments. The highest DMT (832 mg plant^{-1}) was exhibited in the I2 treatment whilst the lowest DMT (482 mg plant^{-1}) was translocated to grain under the I4 treatment conditions (water limitation from anthesis to grain filling stage). The highest DMT observed under moderate water deficit conditions (I2) was in agreement with the results of Zhang *et al.* 2008, but not with those reported by Nazeri (2005) and Ghodsi (2004) on triticale and bread wheat cultivars, respectively. On the other hand, the reduction of DMT under the I4 treatment, which was shown a critical stage for the remobilization of the stem reserves to the grains, was similarly reported in previous studies by Palta *et al.* (1994), Ghodsi (2004) and Plaut *et al.* (2004).

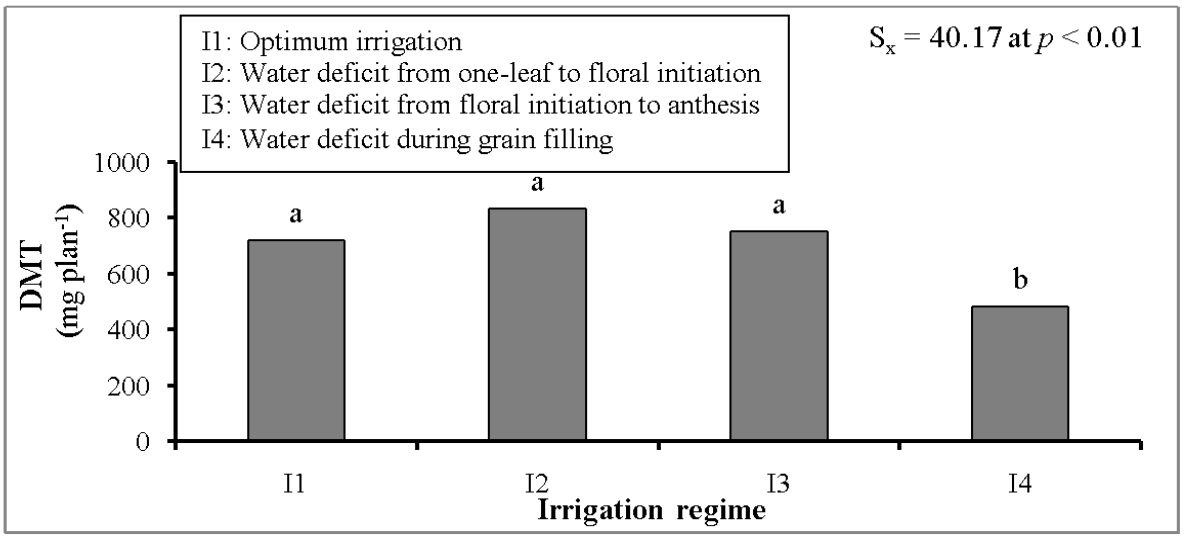

Fig. 5.1. The effect of different irrigation regimes on dry matter translocation (DMT) of durum wheat genotypes

5.3.1.2 Dry Matter Translocation in Durum Wheat Genotypes

The bread wheat cultivar (G3) exhibited the highest DMT (836 mg plant^{-1} compared to the genotype G1 that showed a DMT of 521mg plant^{-1}, although there was no significant difference between the G3 with G2 and G5 durum wheat genotypes (Table 5.1). With regard to the different effects of the genotypes on dry matter translocation in the durum and bread wheat grains during the grain filling, the results of present study, was in agreement with those reported by Inoue *et al.* (2004), Ghodsi (2004) and Álvaroa *et al.* (2008).

Table 5.1 Dry matter translocation (DMT), dry matter translocation efficiency (DMTE), contribution of pre- anthesis assimilates to grain (CPAA), spike dry weight (SPDW), plant height (PLH), spike harvest index (SHI), spike partitioning coefficient (SPC) and grain yield (GY) in different durum and bread wheat genotypes

Genotype	DMT (mgplant-1)	DMTE (%)	CPAA (%)	SPKDW (mg plant^{-1})	SHI (%)	SPC (%)	GY (t ha^{-1})
G1	521.7c	17.8b	56.4b	117b	6.79b	8.12 c	5.1c
G2	801.7a	28.3a	71.5a	121b	8.12a	9.92ab	5.5ab
G3	835.9a	29.2a	64.1ab	136a	8.47a	10.81a	5.6a
G4	635.5b	22.5ab	61b	114d	7.01b	8.97bc	4.9c
G5	685.6ab	25.4a	63.9ab	96c	5.61c	8.23 c	5.2bc
LSD	160	6.95	8.10	8.37	0.88	1.11	0.37
Sx	40.70	1.07	1.24	2.37	0.23	0.28	0.09

Column sharing the same letters indicates no significant differences (at $p < 0.01$)

5.3.1.3 Effect of Water Deficit on Dry Matter Translocation Efficiency and Contribution of Pre- Anthesis Assimilates to Grain in Durum Wheat Genotypes

The dry matter translocation efficiency (DMTE) and the contribution of pre-anthesis assimilates to grain (CPAA) under optimum irrigation and water deficit conditions manifested different trends in their values (Fig. 5.2). The DMTE exhibited a similar trend as shown with dry matter translocation (DMT) (Figs.5.1 and 5.2). Surprisingly the application of the different irrigation regimes in the I1 to I4 treatments, increased the contribution of the pre-anthesis assimilates to grains (Fig. 5.2).

As shown in Fig. 5.2, the CPAA was 52% under favorable irrigation (I1) and increased to 73.5% under water deficit conditions during the anthesis until late grain filling period. It has been reported that a rapid decrease in canopy photosynthesis after the anthesis, under the terminal drought conditions, caused a reduction in the

contribution of current assimilates to grain filling (Johnson *et al.* 1981). Consequently, a considerable amount of stem reserved carbohydrates are translocated to grains during the grain filling period (Rawson *et al.* 1983; Gent 1994). The 21% increase in CPAA observed in present study is in agreement with the above reports. However, it has been suggested that water limitation itself does not increase the remobilization, but environmental conditions that decrease current assimilation causes a greater requirement for the stem carbohydrate reserves during the grain filling (Kiniry 1993).

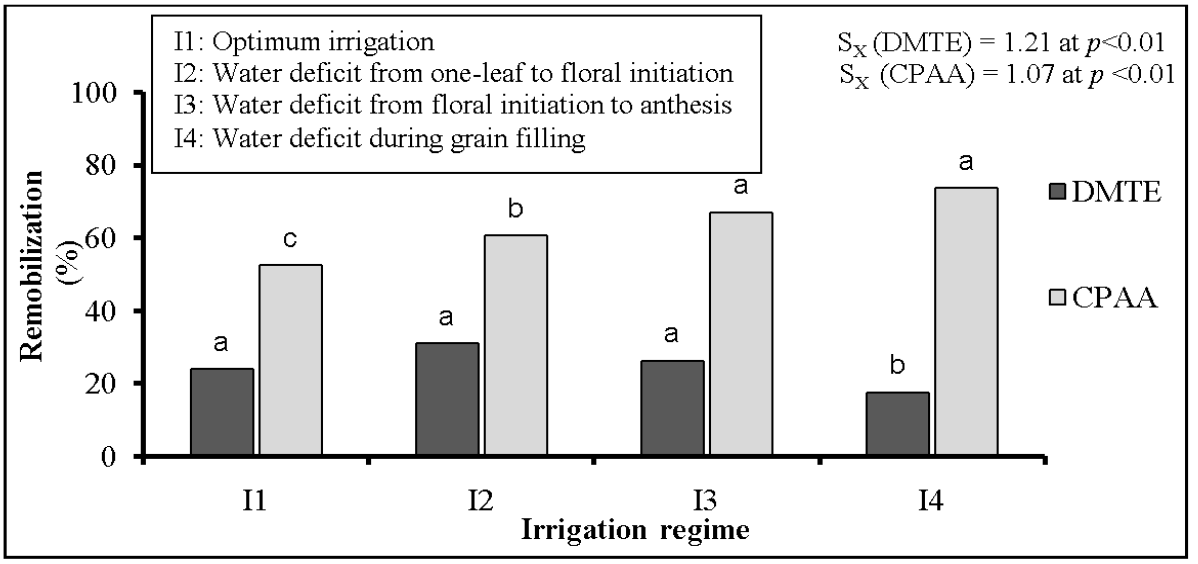

Fig. 5. 2. The effect of different irrigation regimes on dry matter translocation efficiency (DMTE) and contribution of pre- anthesis assimilates to grain (CPAA) in durum wheat genotypes

5.3.1.4 Dry Matter Translocation Efficiency and Contribution of Pre- Anthesis Assimilates to Grain in different genotypes

The effects of genotype on the dry matter translocation efficiency (DMTE) and the contribution of pre-anthesis assimilates to grain (CPAA) as shown in Table 5.1, shows that the G2, G3 and G5 genotypes recorded the higher values. However, the CPAA for the G2 promising durum wheat genotype exhibited highest value amongst all the genotypes studied. Genotypic differences in DMTE and CPAA values has been

reported between and within durum and bread wheat cultivars, which is similar with the results of the present study (Ghodsi 2004; Inoue. *et al.* 2004; Álvaroa *et al.* 2008).

5.3.1.5 Interaction Effect of Water Deficit and Genotype on Remobilization Parameters in Durum Wheat Genotypes

The genotype G2 showed the highest DMTE before and after anthesis under the I3 and I4 water treatments, in addition to being the most stable genotype amongst all the genotypes studied under optimum irrigation and the water deficit conditions (Fig. 5.3). DMTE value changed by only 5%, from 25% to 30%, in G2, while, it changed from 14 to 36 % in G5 genotype. On the other hand, the DMTE for the other genotypes, except for genotype G3, decreased significantly under the I4 (water limitation from anthesis to grain filling) treatment.

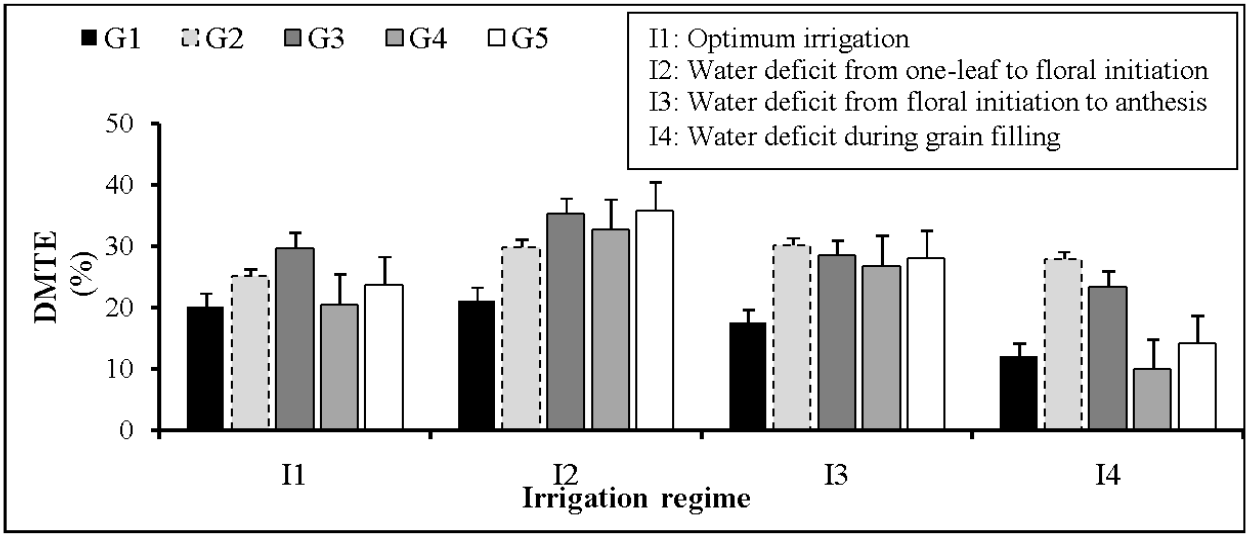

Fig. 5.3. Interaction effect of water deficit and genotype on dry matter translocation efficiency (DMTE) in durum wheat genotypes. Results are shown as mean ± standard error ($p<0.01$), obtained from three replicates

The interaction effect of genotype and water deficit (Fig. 5.4) on the contribution of the pre-anthesis assimilates to grain (CPAA), showed that the CPAA increased considerably with the application of water deficit during the I2 (one-leaf to floral initiation), I3 (floral initiation to anthesis) and I4 (anthesis to late grain filling) for all

the genotypes studied. However, the CPAA value surprisingly increased in the G2 durum wheat genotype under the I3 and I4 water deficit conditions compared to the other genotypes, similar to the reports of Inoue *et al.* (2004) and Álvaroa *et al.* (2008) on bread and durum wheat cultivars. This suggests that the superior characteristics of the G2 genotype in relation to the remobilization of pre-anthesis assimilates during grain filling makes it a good candidate as a durum wheat drought tolerance genotype in the future. Several researchers have confirmed that the water soluble carbohydrates in stems contribute the main carbon source for grain yield under terminal limited photosynthetic conditions due to drought stress during the grain filling. It has also been introduced as a physiological indicator related to drought tolerance (Diab *et al.* 2004; Ehdaie *et al.* 2006; van Herwaarden *et al.* 2006).

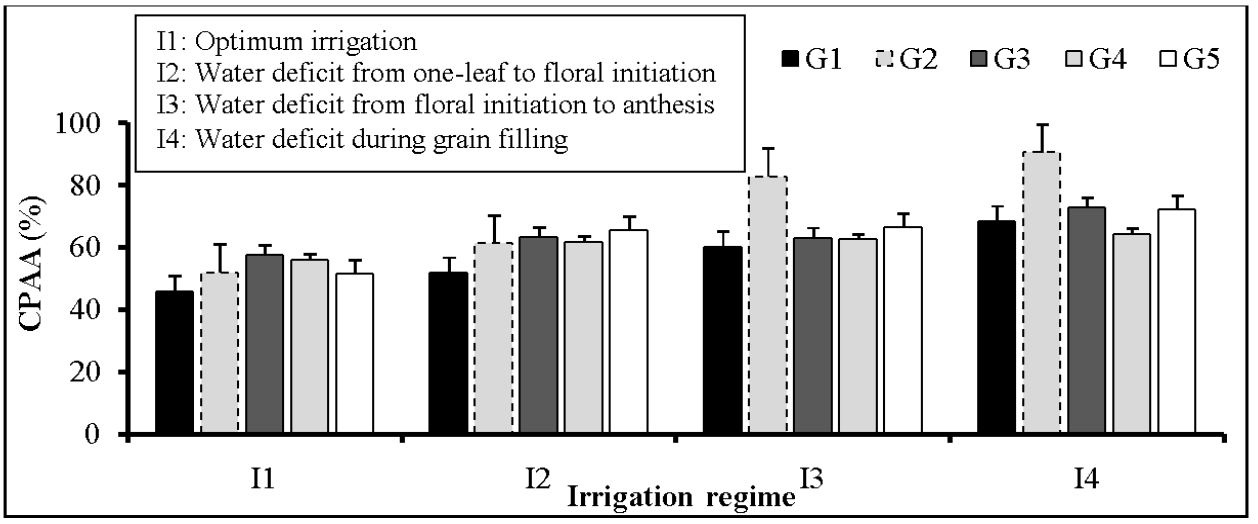

Fig. 5.4. Interaction effect of water deficit and genotype on the contribution of pre-anthesis assimilates (CPAA) to grain in durum wheat genotypes displays. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

The important and considerable role of plant source and sink in the remobilization of the pre-anthesis assimilates to grain is well known and documented and thus an investigation on the effective parameters for improving their capacity during different plant growth and developmental stages can help to increase remobilized carbohydrates (Kuhbauch and Thome 1989; Blum 1996). It has been demonstrated that

under optimum conditions, the stem reserve accumulation can become the main source of adequate carbohydrate storage before the grain filling period, depending on the plant traits improved at the pre-anthesis (Yang *et al.* 2001; Plaut *et al.* 2004). Therefore, longer days to heading and plant height in the G2 and G3 genotypes in comparison with the other genotypes studied under the optimum moisture conditions could have an effect on enhancing stem carbohydrate reserves before the heading stage (Table 5.1). On the other hand, to have a sizeable sink increasing requirement and demand for translocation of assimilates to grain. Spike dry weight, spike harvest index and spike partitioning coefficient which are known as the sink capacity indices (Blum 1996; Slafer 1996) exhibited higher values in the G2 and G3 genotypes compared to the other genotypes (Table 5.1). Consequently, a strong source and sink effect and their balance in these genotypes have improved remobilization parameters and enhanced the contribution of pre-anthesis assimilates to grain during grain filling in the G2 genotype and Chamran bread wheat cultivar (Fig. 5.2 and Table 5.1). The lower reduction in grain yield observed in the G2 and G3 genotypes during grain filling under water deficit conditions was probably due to the dominant remobilization traits in these genotypes compared to the other genotypes studied (Fig. 5.5 and Table 5.1).

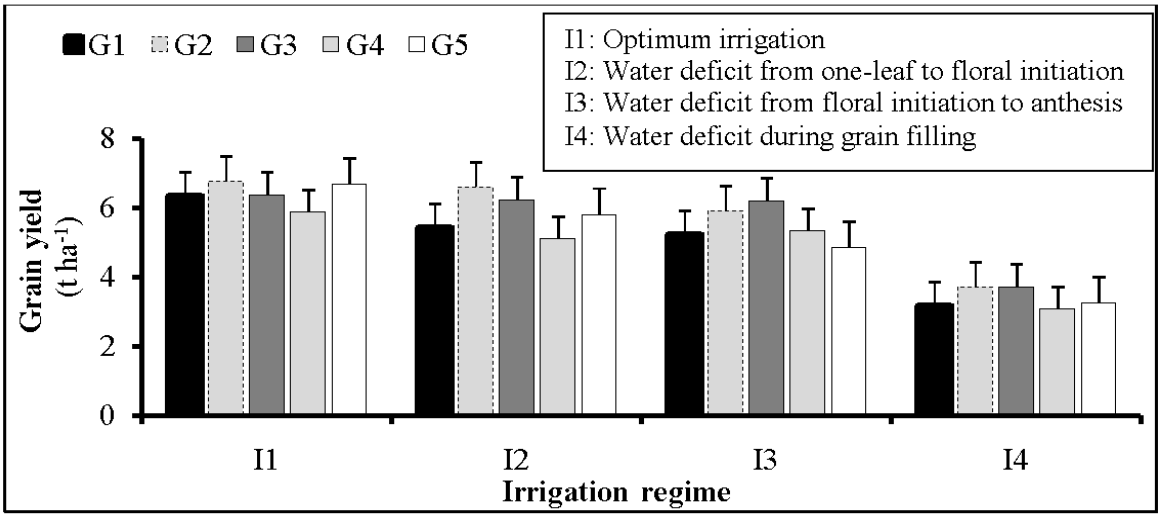

Fig. 5.5. Interaction effect of water deficit and genotype on grain yield in durum wheat genotypes. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

5.4 CONCLUSIONS

The results from present study indicated that although the contribution of pre-anthesis assimilates to the grain increased early growth stage until grain filling period under water deficit conditions but both dry matter translocation and dry matter translocation efficiency decreased during the floral initiation to grain filling. The highest assimilate contribution was made under I3 water limitation condition while dry matter translocation and dry matter translocation efficiency exhibited the lowest values at those stage. Amongst genotypes studied, the G2 and G3 bread wheat genotypes exhibited the maximum parameters due to remobilization. Particularly, the contribution of pre-anthesis assimilates to grain enhanced in the G2 genotype during the grain-filing period. It appears that higher growing degree-days (greater day to heading) and plant height under optimum moisture conditions could have an effect on enhancing stem carbohydrate reserves before the heading stage. On the other hand, the spike dry weight, SHI and SPC, as the plant sink capacity indices, indicated higher values in the G2 and G3 genotypes. Consequently, the strong source and sink and their balance in these genotypes improved remobilization and hence enhanced the contribution of pre-anthesis assimilates to grain during the grain-filling period. In addition to this, the lower reduction in grain yield during grain filling under water deficit conditions observed in the G2 and G3 genotypes could be due to dominant remobilization in these genotypes.

CHAPTER 6

DROUGHT-INDUCED CHANGES ON PHENOTYPE, YIELD AND YIELD COMPONENTS OF DURUM WHEAT GENOTYPES

6.1 INTRODUCTION

Water is the largest component in the make-up of plants and serves as the solvent, which transports minerals and dissolved carbohydrates throughout the plant. However, the ecological and physiological responses of plants to water limitation vary during their growth and at its different developmental stages. Thus an investigation of the plant response to drought at its different developmental stages can be useful to overcome the negative effects of water stress in plants (Casati and Walbot 2004; Dai and Li 2004; Guo *et al*. 2004; Jones-Rhoades and Bartel 2004; Canadian Food Inspection Agency 2006; Passioura 2007).

Drought is a major limiting factor affecting crop production in addition to other environmental stresses, particularly high temperature, salt, acid and cold stresses. The negative effect of drought stress on yield and yield components has been well documented as a major problem in many developed and developing countries (Hernandez *et al* 2004; Guo *et al*. 2004; Passioura 2007).

Developing crops with suitable advantages under water stress conditions is a basic challenge for wheat improvement programs. In addition to this, it has been suggested that one important strategy for crop production, yield improvement, and yield stability is to develop drought tolerant crop varieties under water deficit conditions (Siddique *et al*. 2000). Amongst crop plants, wheat cultivation inadvertently faces drought conditions under arid and semi arid regions. It is widely consumed by humans in producer countries and other countries where wheat cannot be grown. About 95% of the wheat grown worldwide is bread wheat (Shewry 2007 and Dixon *et al*. 2009). The durum wheat (*Triticum turgidum durum*) with a global production of 30 million ton, is an important adapted crop under drought conditions, particularly in the Mediterranean

region where 75% of the world's durum grain is produced (Araus *et al.* 2003; Condon *et al.* 2004).

Among plant characteristics, tillering capability is considered as one of the main plasticity traits in response to different environmental conditions. It is a remarkably important trait in cereals because the potential number of tillers, fertile (productive) tillers and also tillers survival changes with genetic factors and environmental conditions (Mosaad *et al.* 1995; Acevedo *et al.* 2002). With regard to genetic factors related to tillering, De Vita *et al.* (2007), Slafer and Araus (2007) reported that the genetic gains of durum wheat have mainly been assigned to a balanced improvement in fertility because of higher assimilates to the growing tillers and spikes. This caused a general increase in total biomass production, with the harvest index remaining practically unchanged.

It has been reported that low tillering ability in wheat genotypes showed a close association between the number of fertile tillers and grain yield. However, there was an inverse relationship between the number of fertile tillers and 1000-grain weight (Valério *et al.* 2009; Ozturk *et al.* 2006). Furthermore, Mosaad *et al.* (1995) reported that tillering is the main yield component in bread and durum wheat and consequently their grain yield are significantly affected under water limitation conditions. In addition to this, the results of growth-room experiments by Izanloo *et al.* (2008) revealed that grain number per spike and the percentage of aborted tillers were the major components that affected wheat grain yield under water stress.

Environmental stresses particularly water deficit can cause different changes in spike characteristics and its related reproductive traits, and those are important organs in crop production and also yield and yield components. Many researchers have reported that water limitation at different growth stages affected the number of total and fertile

spikelets and florets (Rahman *et al.* 1977; Blum and Pnuel 1990; Saini and Westgate 2000; Casati and Walbot 2004; Ghodsi 2004; Canadian Food Inspection Agency 2006). In addition, Blum and Pnuel (1990) reported that water limitation during the terminal spikelet to booting stage considerably decreased the number of spikelets per spike. Other studies have shown that the number of grain spike^{-1} has a predominant importance over grain weight in defining yield in high latitudes (Peltonen-Sainio *et al.* 2007) whereas grain weight is well known as a major yield component, determining final yield in certain Mediterranean environments (García del Moral *et al.* 2003).

Water use efficiency (WUE) has been defined differently depending on the authors. According to Fisher (1979), it is often considered as being the relationship between dry matters produced per unit of water transpired (Blum 2005). Nevertheless, because of importance of increasing water use efficiency in crop production that is resulted in reducing stress on the ground water resources, agriculture must aim to improve all aspects of water management as well as developing crop cultivars with a higher efficiency of water utilization (Turner 1993).

Blum (2005) reported that water use efficiency was the same in high-yielding semi-dwarf and landrace of durum wheat cultivars in control condition, while it increased under water deficit condition. It has been indicated that the cultivars with higher grain production tended to have higher WUE. In addition, water use efficiency was significantly correlated to grain yield and harvest index in wheat, especially to the yield. Furthermore, it was shown by Zhang *et al.* (2009) that greater values for less irrigated treatments and highest grain production was achieved under moderate water deficit.

It has been shown that WUE increased substantially from 1 - 1.2 kg m^{-3} for wheat cultivars from the early 1970 s to 1.4 - 1.5 kg m^{-3} for recently released cultivars. There was

also a variation in yield and WUE of about 20 % among old and modern cultivars (Zhang *et al.,* 2009). Additionally, results from Zhang *et al.* (2009) also showed that for better yield and WUE, crops might not need full irrigation.

The ability of crop cultivars to perform reasonably well in variable rainfall and water stressed environments is an important trait for stability of production under drought stress conditions. Therefore, several selection criteria have been proposed for selecting genotypes based on their performance in stress and non-stress environments. Among the stress tolerance indicators, a larger value of tolerance index (TOL) and stress susceptibility index (SSI) represent relatively more sensitivity to stress, thus a smaller value of TOL and SSI are favored. Selection based on these two criteria favors genotypes with low yield potential under non stress conditions and high yield under stress conditions. On the other hand, selection based on stress tolerance index (STI) will be resulted in genotypes with higher stress tolerance and yield potential will be selected He defined stress tolerance index which can be used to identify genotypes that produce high yield under both stress and non-stress conditions (Fernandez 1992).

The principal aims of this research were to:

1. Study the tillering behaviors in order to understand the susceptible stages of growth and tolerant genotypes to different water deficit conditions
2. Investigate the spike traits related to drought tolerance at different growth and developmental stages
3. Determine the yield and yield components of the durum and bread wheat genotypes under different water deficit conditions
4. Compute the correlation coefficients between yield with the tillering and spike traits

5. Evaluate the water use efficiency among durum and bread wheat genotypes under different water deficit conditions
6. Investigate the screening quantitative indices associated to drought tolerance
7. Introduce the best and stable genotypes using drought tolerance indices based on yield potential

6.2 MATERIALS AND METHODS

6.2.1. Field Experimental Setup

6.2.1 Field Experimental Setup

To investigate the responses of tillering traits, spike characteristics, yield and yield components in durum and bread wheat genotypes under different irrigation regimes, this study was conducted at Khorasan-e-Razavi Agricultural and Natural Resource Research Center (Mashhad Research Station) during 2007-2008 sesons.

6.2.1.1 Soil Analysis and Agronomic Practice

Field soil used in this experiment was analyzed to determine the different parameters at the Soil and Water Research Department (the results have been presented in Appendix1). In addition, meteorological data particularly temperature, rainfall and moisture were recorded at the Mashhad Climatologically Station (Appendix 2). Before sowing, the experimental field was fertilized with 50, 90 and 50 kg NPK ha^{-1}. Additionally, 70 kg N was top-dressed and split into two applications. To prevent the occurrence of diseases, the experimental seeds were coated with Vitavax fungicide (Carboxin Thiram) which was used at two g kg^{-1} seed before planting. Moreover, weeds were chemically controlled by 2, 4 - D (2, 4-dichlorophenoxyacetic acid) at the end the tillering stage by 2 L ha^{-1}. Each plot consisted 12 rows 3 m in length and spaced 20 cm apart. Therefore, the subplot size was calculated as 7.2 m^2 and the seed density was 450 seeds m^{-2} based on thousands grain weight.

6.2.1.2 Seed Materials

The seeds (G1, HAI-OU - 17 / GREEN - 38; G2, RASCON - 37 / BEJAH - 7; G3, CHAMRAN; G4, RASCON - 39 / TILO - 1; G5, GARAVITO3/ RASCON37 // GREEN8) were obtained from the elite durum yield trials (EDYT) during 2006-2007 in the Seed and Plant Improvement Institute (SPII) Iran (Appendix 3). However, they were tested again under different osmotic stress conditions using polyethylene glycol at the laboratory of University of Malaya. Amongst the seeds studied under laboratory experiment condition, two durum wheat genotypes G2 and G4 were screened out, based on stress tolerance indices, as severe and moderate drought tolerant genotypes while G1 and G5 were applied as susceptible durum wheat genotypes. In addition to these, Chamran bread wheat (G3) which is recognized as a drought tolerant cultivar was used to compare the drought tolerance traits amongst the genotypes. Appendix 6 presents some characteristics and pedigree of these 5 durum and bread wheat genotypes used in the current study.

6. 2.1.3 Experimental Design and Treatments

Five genotypes screened out from the germination experiments were used under different irrigation regimes. The experiments were laid out in split-plot arrangement based on a complete randomized block design with three replications. Irrigation regimes were considered as the main plots (included four levels) and sub-plots were assigned to five genotypes. Irrigation regimes (I1, I2, I3, and I4) were similar to those explained in part 4.2.1.

6.2.2 Measurements

6.2.2.1 Tillering Traits

In order to uses the tiller conting, five plants were randomly chosen from each plot at the start of the flag leaf stage. Then at the laboratory, the roots of the selected plants were washed and separated carefully to provide a single plant sample. Thereafter, the average of total number of tillers (TNT) of each single plant was counted. In addition to this, the number of fertile (productive) tillers (NFT) was also determined at the maturity stage. From the obtained TNT and NFT values, the tiller survival percentage (TSP) was calculated as follows:

$$TSP\ \% = (NFT / TNT) * 100$$

6.2.2.2 Spike Traits and Characteristics

In order to compute spike traits, twenty plant stems (including leaves and spikes) were randomly selected from each plot at anthesis and physiological maturity stages. The samples were kept in an oven for 3 days at 80 °C and finally, the shoot and spike dry weight, the number of spikelets per spike, the number of total and potential florets per spike, and also the spike length were accurately measured in laboratory. In addition to this, the spike partioning coefficient (SPC) and spike harvest index (SHI) were calculated according to Donalson (1996) Robertson and Giunta (1994) as follows:

$$SPC\ \% = (SPKDWa / DMA) * 100$$

$$SHI\ \% = (SPKDWa / DMM) * 100$$

where, SPKDWa is spike dry weight at anthesis stage, DMA and DMM are shoot dry matter at anthesis (leaves+ stem) and physiological maturity (leaves+ stem+grain) stages, respectively.

6.2.2.3 Number of Spikes m^{-2}

An area of 0.5 m^2 was selected randomly at 4 locations in each plot to count the total number of spikes. The average value was used in the statistical analysis.

6.2.2.4 Number of Grain $Spike^{-1}$ and 1000 Grain Weight (g)

Twenty spikes at harvesting time were selected at random from each plot at 4 places. Each spike was threshed separately and the grains of each spike were counted and averaged in order to calculate the grain numbers $spike^{-1}$. A thousand grains were counted at random and their weight determined.

6.2.2.5 Final Plant Height (cm)

Twenty plants were selected at the maturity phase from each plot in 4 places for height determination in cm.

6.2.2.6 Days to Heading (DH) and Maturity Duration (MD)

The number of days from planting to heading (at the 50% of heading in the field) was recorded for each plot of. Additionally, the duration of the anthesis to physiological maturity stage was determined as maturity duration.

6. 2.2.7 Grain and Biological Yield (t ha^{-1})

To avoid statistical error arising from border effects, 6 rows of each plot were removed and the remaining rows, 7.2 m^2, were harvested using a plot combine harvester (NMELITE, Wintersteiger Seed Mech). The grain weight and biological yield were recorded in kg and then converted into ton ha^{-1}. Biological yield (biomass) was recorded by weighing of the plant dry matter (above ground) in each experimental plot.

6.2.2.8 Water Use Efficiency

Total water use was identified from initial soil water content minus final soil water content, precipitation, irrigation, runoff, drainage, and capillary rise using the following equation (Zhang *et al.* 1999):

$$TWU = P + I + \Delta W - R - D + CR$$

where TWU is total water use through duration of crop growth (mm), P is precipitation (mm), I is irrigation (mm), ΔW is soil water content (when the crop is sown minus that at harvest for the 2-m depth, mm), R is run off (mm), D is drainage from the root zone (mm), and CR is capillary rise to the root zone (mm). Due to the deep soil profile and large water-holding capacity, runoff was never observed in the experiment field. In addition to this, findings of Zhang *et al.* (1999) and Keshavarz *et al.* (2006) in the arid and semi arid regions revealed that drainage and capillary rise were insignificant and are not considered further. Consequently TWU was used under current experimental conditions as follow:

$$TWU = P + I + \Delta W$$

Water use efficiency (kg m^{-3}) was defined as crop yield divided by total water use, where Y is grain yield or biological yield (kg ha^{-1}) as follow:

$$WUE = Y / TWU$$

6.2.2.9 Drought Tolerance

Using yield potential (YP) and stress yield (YS), the following quantitative criterias of drought tolerance were calculated:

6.2.2.9.1 Stress Susceptibility Index (SSI)

$$SSI = [1 - (Ys) / (Yp)] / SI$$

$$SI = (1 - \acute{Y}S / \acute{Y}P)$$

where, SI is stress intensity, ÝS and ÝP are the mean yield over all genotypes evaluated under stress and non-stress conditions, respectively (Fischer and Maurer 1978):

6.2.2.9.2 Stress Tolerance Index (STI)

$$STI = [(Yp).\ (Ys) / (Yp)^2]$$

This index can be used to identify genotypes that produce high yield under both stress and non-stress environments (Fernandez 1992)

6.2.2.9.3 Tolerance Index (TOL)

$$TOL = YP - YS$$

6.2.2.9.4 Geometric Mean Productivity (GMP)

$$GMP = \sqrt{(YP)\ (YS)}$$

6.2.2.9.5 Mean Productivity (MP)

$$MP = (YP+YS) / 2$$

6.2.2.9.6 Yield Reduction Ratio (Yr)

$$Yr = 1 - (Ys /Yp)$$

6.2.2.9.7 Relative Performance (PR)

$$PR = (YS /YP) / R$$

$$R = (\acute{Y}S / \acute{Y}P)$$

Tolerance index and mean productivity indices were calculated according to Kristin *et al.* (1997) and Fernandez (1992) equations while GMP, Yr and P were estimated based on rosielle and hambling (1981), Golestani and Assad (1998) and Abo-Elwafa and Bakheit (1999) formula, respectively.

6.2.3 Data Analysis

Correlation analyses were computed using SPSS (version 13) software package to determine the relationship among grain yield, yield component, tillering and spike traits. In addition, the final data obtained due to the present experiments were statistically analyzed by MSTAT-C software packages. Data analysed using MSTAT-C and arcsine data transformation was performed for variance uniformity in percentage data. Then all treatments were compared using Duncan's Multiple Range Test ($p < 0.05$ and 0.01) with the values of the least significant digits (Ghodsi 2004; Moosavi *et al.* 2009).

6. 3 RESULTS AND DISCUSSION

6.3.1 Effect of Water Deficit on Tillering

Analysis of variance (as shown in Appendix 13) revealed that effect of irrigation regime was highly significant ($p < 0.01$) for the number of total tillers (TNT) and tiller survival percentage (TSP).

The results of the effect of irrigation regimes on TNT are shown in Fig. 6. 1. Surprisingly, highest TNT was observed in I3, which had water deficit from floral initiation to the anthesis stage, while the lowest TNT value was in the control (I1), which had optimum irrigation.

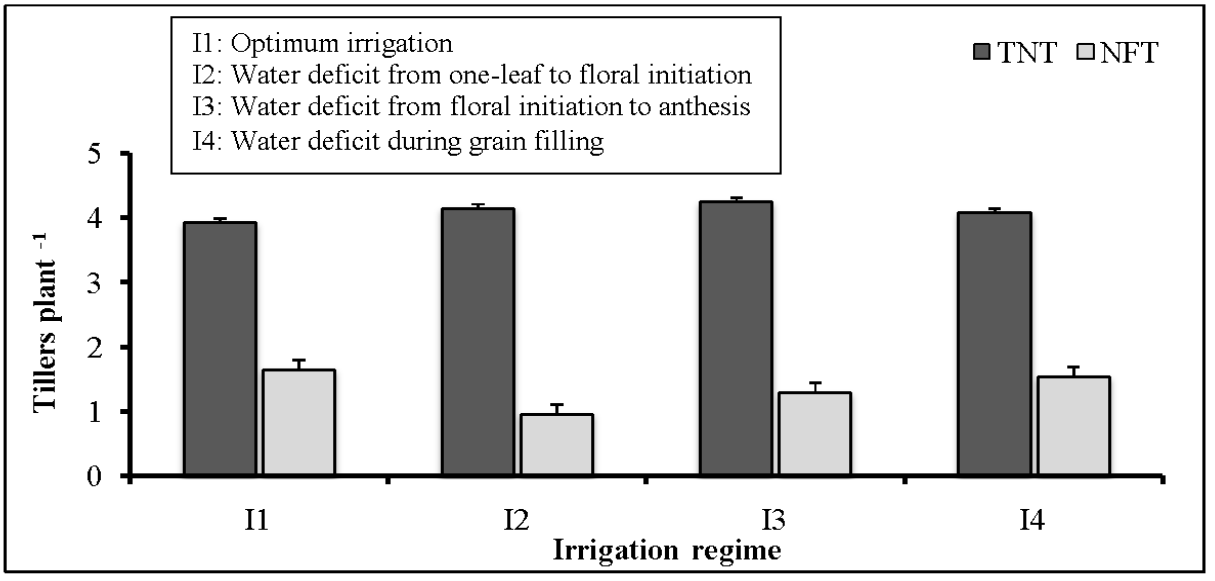

Fig. 6.1. The effect of different irrigation regimes on number of total (TNT) and fertile tillers (NFT) in durum wheat genotypes. Results are shown as mean ± standard error ($p<0.01$), obtained from three replicates

As a result of water limitation, TNT value increased gradually from the one-leaf to the anthesis stage but subsequently decreased significantly after anthesis (Fig. 6.1). As shown in Fig. 6.3, the highest TSP (42%) belonged to I1 (optimum water condition) whilst the lowest value (23%) computed was associated with I2. However, there was no

significant difference between I2 and I4 for this trait. Limitation of water at the one-leaf to floral initiation (I2) and floral initiation to anthesis stages (I3) increased TNT. Bearing in mind that TNT is the total of fertile and unfertile tillers, it seems that the increase in TNT is due to an increase in unfertile tillers under water limitation treatments. This implies that the impact of water deficit on reduction of NFT may be ompensated by increasing TNT at those stages (Figs. 6.1 and 6.4). The compression of tillering traits under different irrigation regimes showed that the sensitivity of NFT to water deficit conditions were more than TNT. It seems that the most susceptible growth and developmental stage to water deficit in NFT was from the one-leaf to floral initiation period among the studied genotypes. The results concurred with the reports of Izanloo *et al.* (2008) who noted that the main yield components, which were associated with yield reduction, were grain number spike^{-1} and number of fertile tillers. Therefore, reduction in grain number and NFT were mainly associated with floret sterility and tiller abortion under water deficit. In addition to wheat, water deficit reduced grain yield in barley (Samarah 2005) by reducing the number of tillers, spikes and grains plant^{-1} and individual grain weight. Post-anthesis water deficit was detrimental to grain yield regardless of the stress severity. The change of TNT under different irrigation regimes conditions in the present study agrees with the findings by other researchers (Mosaad *et al.* 1995; Acevedo *et al.* 2002). Additionally, reports by Maas and Grieve (1990) and Nicolas *et al.* (1993) related to tiller emergence of wheat under water deficit condition confirm these results. However, other studies by Cabeza *et al.* (1993) and García del Moral *et al.* (2003) working on bread and durum wheat have shown that with increasing water deficit, tiller production and survival decreased significantly during different growth and developmental stages. Our results were incongruent with findings of Nazeri (2005) on triticale and Ghodsi (2004) on bread wheat. They reported no significant differences in TNT under water deficit conditions. Overall, the results revealed that

tillering capability is an important plasticity trait in response to different environmental conditions.

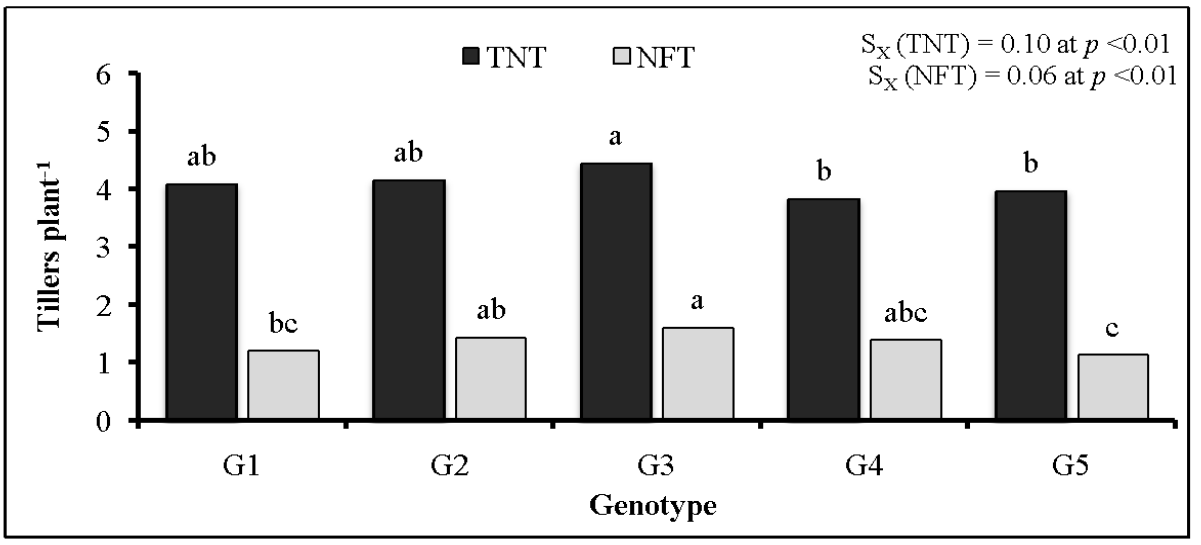

Fig.6.2. Comparison of total number tillers (TNT) and fertile tillers in different durum and bread wheat genotypes

6.3.2 Tillering Behavior in Different Genotypes

The analysis of variance (Appendix 13) indicated that genotypic effect was significant at $p < 0.05$ for both the number of fertile tillers (NFT) and tiller survival percentage (TSP), while number of total tillers (TNT) was significant at $p < 0.01$.

Figure 6.2 shows the different TNT and NFT values in various durum and bread wheat genotypes. The Chamran bread wheat (G3) cultivar exhibited the maximum TNT and NFT values, while G4 and G5 durum wheat genotypes produced the lowest values for TNT and NFT, respectively. In addition, there was a significant difference for TNT between Chamran cultivar and all the other durum wheat genotypes. However, there was no significant difference between G1 and G2 durum wheat genotypes. The effect of genotype on TSP was similar to those shown in NFT (Fig. 6. 2). Overall, G3, G2 and G4 showed a higher TSP than G1 and G5. The variation effects of genotypes on tillering traits have been previously reported by Acevedo *et al.* (2002), Ghodsi (2004), Izanloo *et al.* (2008), Valério *et al.* (2009) in bread wheat, Nazeri (2005) in triticale, De

Vita (2007), Slafer and Araus (2007) in durum wheat and Samarah, (2005) in barley. They reported that various genotypes showed different values of TNT and NFT under different environmental conditions, similar to the present study (Fig. 6.2).

The findings indicated that significant differences existed among the various genotypes studied in relation to the irrigation treatments. In general, apart from the Chamran bread wheat cultivar, which produced the highest values of TNT, NFT and TSP amongst all the genotypes, G2 performed the highest values amongst the durum wheat genotypes studied (G1, G4 and G5). With regard to G3, this was recognized as a drought tolerant cultivar (Ghodsi 2004), its preference compared to all the other studied genotypes is related to its tillering traits, which are suitable characteristics for drought tolerance under water deficit conditions. Therefore, it can be suggested that the G2 genotype, which exhibited similar results to that of the G3 genotype related to tillering traits may be introduce as a durum wheat drought tolerant genotype. Nazeri (2005) and Ghodsi (2004) also reported similar results for TSP in triticale and bread wheat, respectively. In addition, findings of Izanloo *et al.* (2008) showed that there were different tillering responses in genotypes under different water deficit conditions. The genotypes, which produced a high number of tillers, aborted large numbers of tillers under water deficit.

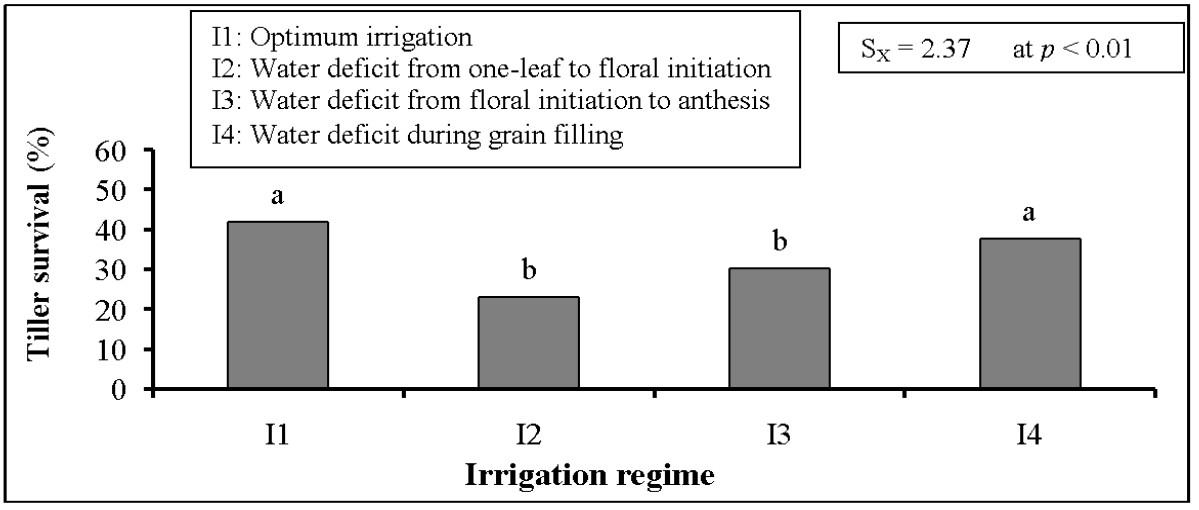

Fig. 6.3. The effect of different irrigation regimes on tiller survival percentage in durum wheat genotypes

6.3.3 Interaction Effects of Genotype and Irrigation Regimes on Tillering Traits

The analysis of variance (as shown in Appendix 13) revealed that the interaction effect of genotype and irrigation regime was highly significant at ($p < 0.01$) for TNT and significant at ($0 < 0.05$) for NFT and TSP. In this study, G5 exhibited the lowest value for all tillering traits under I2 while G3 and G2 gave the highest values for TNT and NFT traits, respectively (Figs. 6.4 and 6.5). A comparison of the interaction effects between TNT and NFT (Figs. 6.4 and 6.5) showed different trends for tillering traits under water deficit conditions. TNT increased under I2 and I3 treatments. Besides, I2 caused a severe reduction in NFT. However, NFT increased because of water limitation in I3 compared to I2 treatment. Thus, the most susceptible stage of growth durum wheat due to NFT was limitation of irrigation during two leaf and floral initiation (I2). In addition, Chamran (G3) displayed the lowest NFT under optimum irrigation compared to durum wheat genotypes. However, G2 produced higher NFT values in both optimum and water deficit conditions. In addition, the results of the Fig. 6.4 using by standard error display that the most stable genotype under different irrigation regimes due to NFT was G2, while G1 and G5 were unstable genoyypes for NFT trait under normal irrigation compared to water deficit condition.

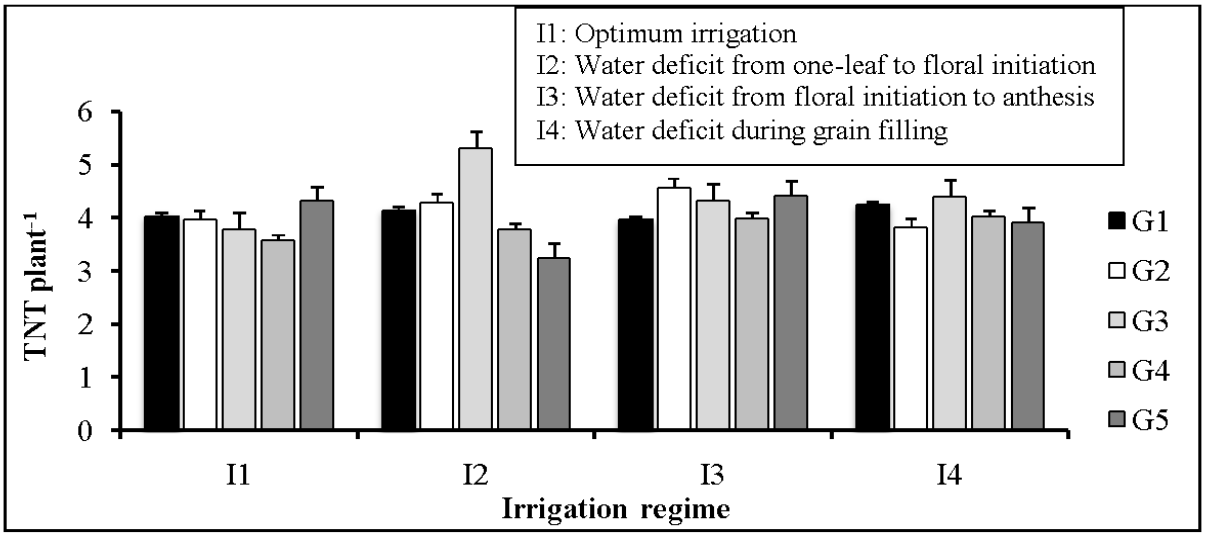

Fig. 6.4. Interaction effect of irrigation regimes and genotype on total number of tillers (TNT). Results are shown as mean ± standard error ($p<0.01$), obtained from three replicates

Researchers believe that determinate tillering under optimum conditions is a very important characteristic in durum and bread wheat (Izanloo *et al.* 2008; Valério *et al.* 2009). Their results showed that by increasing the number of tillers under optimum conditions, mortality of the tillers increased under water stress conditions, which confirmed our results under optimum and water deficit conditions. They also found a close association between NFT and grain yield in low tillering ability of the wheat genotypes under optimum irrigation. This indicated that ability to determine tillering under optimum conditions could be a suitable characteristic for determining a drought-tolerant cultivar.

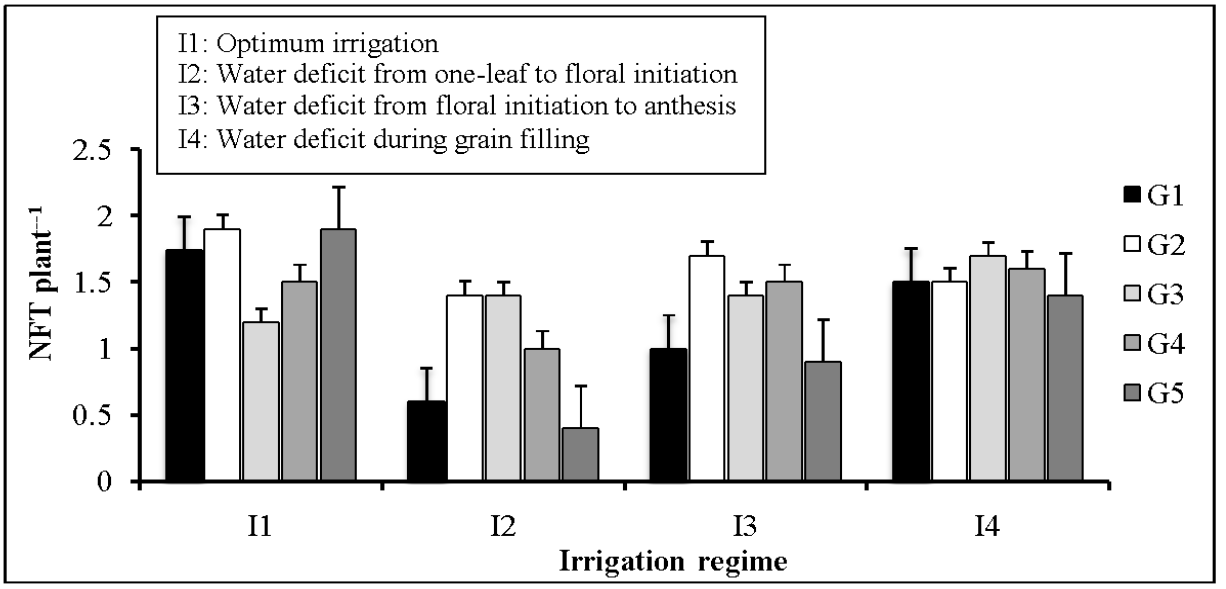

Fig. 6.5. Interaction effect of irrigation regimes and genotype on number of fertile tiller (NFT). Results are shown as mean ± standard error (p<0.01), obtained from three replicates

6.3.4 The Relationship between Tillering Traits and Grain Yield

Results of simple correlation analyses from the data of tillering traits and grain yield are shown in Table 6.1. The NFT showed the highest and lowest correlation coefficients with TSP (r = 0.836**) and grain yield (r = 0.003), respectively. Apart from the negative correlation between TSP and the TNT and grain yield, all traits

exhibited a positive correlation. Grain yield correlated positively with TNT and NFT but correlated negatively with TSP. Furthermore, TSP was positively ($p < 0.01$) correlated with the NFT but negatively correlated with the TNT.

Several workers have been suggested the importance of association between grain yield and tillering capacity, which are related to the first developmental processes during early growth stages (Mosaad *et al.* 1995; Miralles *et al.* 2000; Larbi and Mekliche 2004; García del Moral *et al.* 2003). In addition, a positive correlation of grain yield and NFT was confirmed by findings of the following researchers. Their results indicated the reduction of grain yield under water deficit in barley (Samarah 2005) and bread wheat (Izanloo *et al.* 2008) was due to reduced NFT and grains per plant. In addition, Valério *et al.* (2009) report those low tillering ability genotypes showed a closer association of NFT with grain yield. However, the results of Akram *et al.* (2008) revealed a negative correlation between tillers and spike length with grain yield at phenotypic and genotypic levels.

Table 6.1 Correlation coefficients among tillering traits and grain yield of durum and bread wheat genotypes under different water deficit conditions

Traits		TNT	NFT	TSP	GY
Total number of tillers	(TNT)	1	0.331	- 0.095	0.105*
Number of fertile tillers	(NFT)		1	0.836**	0.003*
Tiller survival percentage	(TSP)			1	-0.060
Grain yield	(GY)				1

* Correlation is significant at $p < 0.05$ ** Correlation is significant at $p < 0.01$

6.3.5 Effect of Water Deficit and Genotype on Number of Spikelets

The analysis of variance (as shown in Appendix 14) revealed that effect of irrigation regime and interaction effect of the irrigation regime and genotype were significant ($p < 0.05$) for the number of spikelets spike^{-1} (SPKE), while genotypic effects was highly significant ($p < 0.01$). The highest SPKE was observed in the I2 irrigation treatment, which was affected by water limitation from the one-leaf to floral initiation stage, while the lowest SPKE value belonged to the I3 irrigation treatment (water limitation from the floral initiation to anthesis). However, there were no significant differences between optimum irrigation (I1) with I2 and I4 for SPKE. Therefore, the most susceptible stage to drought stress was during floral initiation to anthesis, which was similar of the Blum and Pnuel (1990) reports. They revealed that water deficit between the terminal spikelets and the boot stage decreased the spikelet number per spike remarkably (Table 6.2).

Table 6.2 Response of spikelets spike^{-1} (SPKE), number of potential florets spike^{-1} (NPF), spike length (SPKL), spike dry weight (SPKDW), spike partitioning coefficient (SPC), days to heading (DH) and spike harvest index (SHI) and leaf area index (LAI at terminal spikelets) under different irrigation regimes

Traits	SPKE	NPF	SPKL (mm)	SPKDW (mg)	SPC (%)	DH	SHI (%)	LAI
Irrigation regime								
I1	15.13 ab	54.9 ab	67.7 ab	146.6 a	10.0 a	118a	7.9a	2.2 a
I2	15.17 a	51.9 ab	69.6 a	115.2 c	9.2 b	113b	7.5 a	2.1bc
I3	14.43 c	50.8 b	65.3 b	81.9 d	6.4 c	118a	4.9 b	1.9c
I4	15.01 b	56.1 a	69.9 a	124.1 b	10.2 a	118a	8.4 a	2.2 a
LSD	0.16	4.22	3.18	6.13	1.54	3.71	1.10	0.19
Sx	0.02	0.80	0.92	1.17	0.29	1.07	0.20	0.07

Column sharing the same letters indicates no significant differences at $p < 0.01$

6.3.6 Effect of Water Deficit and Genotype on Potential and Total Florets

The nalysis of variance revealed that, apart from the number of total floret (NTF), which was not significantly different under irrigation regimes, both the potential (NPF) and total florets traits were highly significant due to genotype and their interaction effects (Table 6.3). Besides, the NPF was also significantly affected under water deficit conditions. The response of the NPF under different irrigation regimes indicated that the highest negative effect of water limitation was made during the floral initiation to anthesis stage (I3), while the lowest negative effect belonged to the I4 treatment (Table 6.2).

With regard to fertility of the florets before anthesis in wheat, water limitation during floral initiation to anthesis caused the highest reduction of NPF compared to other irrigation regimes. Conversely, water deficit after anthesis (I4) caused the lowest negative effect on the NPF (Table 6.2). Regarding to the significant effect of genotype on the NTF and NPF as shown in Table 6.3, the highest NTF and NPF were produced by G1 whilst the lowest values for both traits belonged to the G5 genotype. Generally, there was a similar trend concerning the NTF and NPF among the different genotypes (Table 6.3).

As shown in Table 6.3, the response of the spikelets was different among durum and bread wheat genotypes. Bread wheat genotype (G3) exhibited the maximum value (16 SPKE), whereas G5 (durum wheat) showed the minimum value of spikelets spike^{-1} (14 SPKE) among the five studied genotypes. However, there was no significant difference between G3 and G2.

Table 6.3 Response of spikelets spike^{-1} (SPKE), number of total florets spike-1 (NTF) number of potential florets spike^{-1} (NPF), spike length (SPKL), spike dry weight (SPKDW), spike partitioning coefficient (SPC) , day to heading (DH) and spike harvest index (SHI) in different durum and bread wheat genotypes

Traits	SPKE	NTF	NPF	SPKL (mm)	SPKDW (mg)	SPC (%)	DH	SHI (%)
Genotype								
G1	14.7 bc	92.8 a	58.8 a	64.3 b	116.9 b	8.12 c	118ab	6.79b
G2	15.6 ab	86.1 b	57.0 ab	61.4 b	121.2 b	9.92ab	119 a	8.12a
G3	16.2 a	812 c	51.1 bc	89.5 a	136.2 a	10.81a	116 b	8.47a
G4	14.6 c	77.5cd	51.8 bc	62.3 b	114.7 b	8.97bc	116 b	7.01b
G5	14.2 c	73.4 d	48.3 c	63.0 b	95.8 c	8.23 c	115 b	5.61c
LSD value	0.91	6.64	6.09	3.97	8.37	1.11	2.65	0.88
Sx	0.23	0.01	1.57	1.02	2.16	0.28	0.92	0.23

Column sharing the same letters indicates no significant differences at $p < 0.01$

6.3.7 Effect of Water Deficit and Genotype on Spike Length

As shown in Appendix 14, apart from the irrigation regime, which was significantly different ($p < 0.05$) for spike length, effect of genotype and interaction effects were highly significant for this trait. Table 6.2 show that spike length is affected by water limitation at different growth stages. Similar to NPF, the most susceptible stage to water deficit in durum and bread wheat genotypes was the I3 treatment. Hence, the lowest value for spike length (65 mm) was observed in I3 whereas the highest (70 mm) was obtain under I4 treatment. However, there was no significant difference between the I4 and I2 treatments. With regard to genotypic effects, genotype G3 (bread wheat) exhibited a remarkable variation in spike length compared to the other studied

genotypes (Table 6.3). However, there was no significant difference in spike length amongst the durum wheat genotypes (G1, G2, G4, and G5). Although, spike length shows some stability under different conditions, the results of the present study demonstrated that it decreased significantly under water deficit during the floral initiation to anthesis period, which is congruent with the reports of Iqbal *et al.* (1999) on durum wheat and Ghodsi (2004) on bread wheat. Overall, the reduction of the spike length under water stress conditions causes a decrease in some of the spike traits. It can therefore cause some changes in the number of spikelets and florets per spike. For this reason, it is clear that the reduction of SPKE and NTF under I3 treatment, are strongly related to the decrease in spike length (Table 6.2).

6.3.8 Effect of Water Deficit and Genotype on Spike Dry Weight

Analysis of variance for spike dry weight (SPKDW) revealed that apart from the interaction effect of water deficit and genotype, which was not significant for spike dry weight, water deficit and genotype effects were highly significant for this trait (Appendix 13). Table 6.3 presents the significant effect of water deficit at different growth and development stages on SPKDW. It decreased remarkably under water deficit conditions compared to optimum irrigation. The highest reduction (66 %) of the SPKDW compared to optimum irrigation was observed under I3 treatment, while the lowest reduction (17 %) was seen under I4 treated plants (Table 6.2). It was found that water limitation during the floral initiation to anthesis stage (I3) severely decreased the SPKDW whereas the effect of water deficit at the earlier (I2) and later growth stages (I4) were comparatively milder which was concurred with finding of Robertson and Giunta (1994). They noted that water deficit treatments reduced spike biomass at anthesis by 58-94% compared to the optimum irrigation.

It seems that significant reduction in the leaf area index under I3 water deficit treatment compared to optimum irrigation had been decreased SPKDW (Table 6.2). With regard to formation of the spike structure during time range of the double ridge to anthesis, which is congruous on the I3 irrigation regime condition, thus any negative effect at this period causes similar impact on the spike traits. Fisher (2001) and Araus *et al.* (2003) revealed that reduction in the LAI under water stress decreases intercepted radiation and partitioning of the photosynthetic matterials to spike. On the other hand, as spike structure formation during terminal spikelets to anthesis stage (Slafer and Whitechurch 2001), the results of the present study confirms that any unfavorable conditions during this period causes a sizable reduction in the spike dry weight value which concur with reports by Robertson and Giunta (1994) and also by Nazeri (2005).

6.3.9 Effect of Water Deficit and Genotype on Spike Partitioning Coefficient

Spike partitioning coefficient (SPC) is an important trait in durum and bread wheat growth as it shows the ratio of photosynthetate partitioned to form the spike. It is calculated based on the spike dry weight to shoot dry weight ratio at anthesis. Hence, it can increase with increasing spike dry weight value or decrease with increasing shoot dry weight. Analysis of variance (Appendix 14) revealed that water deficit, genotype effects and their interactions were highly significant for the spike-partitioning coefficient (SPC). Statistical differences among the irrigation regimes (Table 6.3) indicated that water limitation during the floral initiation to anthesis stage (I3) remarkably decreased the SPC, by about 45 % compared to those under optimum irrigation, whilst there was no significant difference between the I1, I2 and I4 treatments. These results confirm the findings of Ghodsdi (2004), Donalson (1996), Robertson, and Giunta (1994) who also reported that water deficit before anthesis decreased spike dry weight and the spike-partitioning coefficient. However, it had little

effect on the pattern of biomass partitioning to the spike and the proportion of pre anthesis biomass as spike. Thus, any negative effects during the terminal spikelet to anthesis period decreased these crucial spike traits. In addition, the genotype effects on the spike-partitioning coefficient were similar to that on spike dry weight trait described above (Table 6.3).

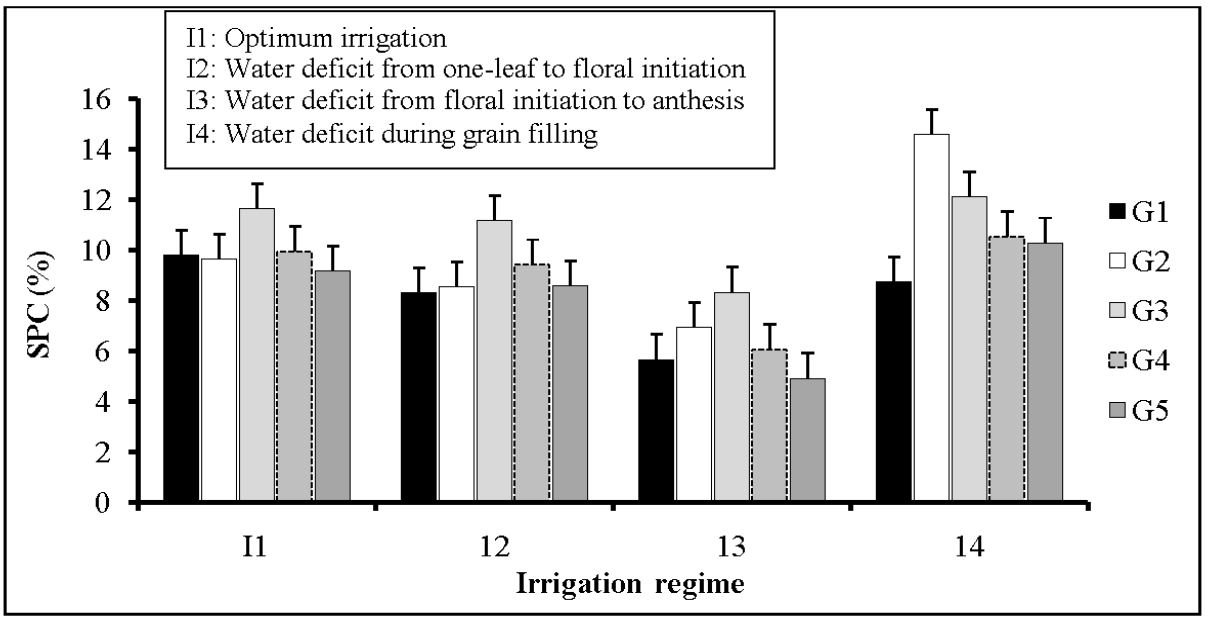

Fig. 6.6. Interaction effect of irrigation regime and genotype on spike partitioning coefficient (SPC). Results are shown as mean ± standard error ($p<0.01$), obtained from three replicates

The interaction effect of the water deficit and genotype on the SPC indicated that genotype G3 (bread wheat) gave the highest SPC under all the irrigation regimes except in the I4 treatment. The genotype G2 showed a higher value, compared to the other durum wheat genotypes under the I3 treatment, which is the crucial period for the SPC and SPKDW traits (Fig. 6.6)

6.3.10 Effect of Water Deficit and Genotype on Spike Harvest Index

Spike harvest index (SHI) is the spike dry weight (at anthesis) to total dry weight ratio at physiological maturity. It shows the proportion of mobilized dry matter to spike in a genotype (Donalson 1996). Analysis of variance (Appendix 14) showed that water deficit, genotype effects and their interactions were highly significant for SHI. The results of present study demonstrated that the effects of water deficit and genotype on SHI were similar to that for spike dry weight and spike partitioning coefficient (Table 6.3). Thus, the lowest SHI value was produced under water deficit conditions during floral initiation to anthesis.

6.3.11 Effect of Water Deficit and Genotype on Number of Days to Heading

As shown in Appendix 14 the analysis of variance revealed that irrigation regime and genotype effects were significant (p <0.05) for the number of days to heading (DH). However, there were no significant differences between optimum irrigation (I1) with I3 and I4 treatments for this trait. Water limitation during one-leaf to floral initiation stage significantly decreased DH (Table 6.2). In other words, the negative effect of water deficit at the early growth and developmental stages can be effective in the reducing DH in the durum and bread wheat genotypes.

6.3.12 The Relationship between Spike Traits and Grain yield

As shown in Table 6.4, Pearson correlation coefficient showed the highest positive relationship between the SHI and SPC (r = 0.95), NPF and NTF (r = 0.88), SPKW and SHI (r = 0.78), SPKE and SHI (r = 0.68), SPKE and SPC (r = 0.63), SPKE and SPKL (r = 0.62), SPKE and SPKDW (r = 0.56), SPKDW and SPKL (r = 0.41), SPKL and SPC (r = 0.40), NPF and DH (r = 0.38), respectively. While relationship

between SPKL and NFT, SPC and DH, SHI and DH, NTF and GY, NPF and GY, SPC and GY were negative and no significant. With regard to the importance of the spike characteristics related on grain yield, there was a positive relationship between the grain yield of the genotypes in present study with SPKE, SPIKE.L, SPKDW and DH whereas it was shown a negative association with NTF, NPF, SPC and SHI. Overall, variations in spike structure and traits were remarkably associated with changes in final grain yield, which confirms previous works by other researchers (Rahman *et al.* 1977; Simane *et al.* 1993; Khazaei 2002; Benmoussa and Achouch 2005).

Table 6.4 Correlation coefficients among spikelets spike^{-1} (SPKE), number of total florets spike^{-1}(NTF), number of potential florets spike^{-1} (NPF), spike length (SPKL), spike dry weight (SPKDW), day to heading (DH), spike partitioning coefficient (SPC), spike harvest index (SHI), spike harvest index (SHI) and grain yield (GY)

Traits	SPKE	NTF	NPF	SPKL	SPKDW	DH	SPC	SHI	GY
SPKE	1	0.34	0.35	0.62**	0.56**	0.009	0.63**	0.68**	0.097
NTF		1	0.88**	0.099	0.328	0.334	0.158	0.158	-0.091
NPF			1	-0.081	0.372	0.384*	0.308	0.368	-0.237
SPKL				1	0.409*	0.204	0.405*	0.375	0.106
SPKDW					1	0.130	0.77**	0.78**	0.145
DH						1	-0.043	-0.101	-0.066
SPC							1	0.95**	-0.333
SHI								1	-0.139
GY									1

*Correlation is significant at p <0.05 ** Correlation is significant at p <0.01

6.3.13 Effect of Water Deficit and Genotype on Biological and Grain Yield

A shown in Appendix 15, the analysis of variance indicated that GY, SPKN, GN, TGW, HI, PLH, DMA and MD significantly at $P < 0.01$ affected under irrigation regime, whilst HI was significant at $P < 0.05$. In addition, the genotypic effect was significant for SPKN, GN, TGW, DMA and significant for BY, GY, HI, PLH at $P < 0.01$. Moreover, interaction effect of irrigation regime and genotype was significant at $P < 0.01$ for SPKN, GN, PLH and significant for TGW.

The results of the present study indicated that different irrigation regimes during growth and developmental stages had different considerable effects on grain yield. The highest grain yield (6.4 t ha^{-1}) was produced under optimum irrigation treatment (I1) whilst the lowest (3.2 t ha^{-1}) was observed in the I4 treatment. Water deficit decreased grain yield at the different growth and developmental stages although the highest negative effect was observed in the I4 treatment. Generally, with water limitation during the different growth and developmental stages (one-leaf to physiological maturity), grain yield decreased gradually from the I2 to I4 treatments. These grain yield reductions were 9%, 15% and 50% under the I2, I3 and I4 treatments respectively, when compared with the optimum irrigation treatment (I1). However, there were no significant differences in grain yield between I2 and I3 water limitation treatments (Fig. 6.7 and Table 6.5).

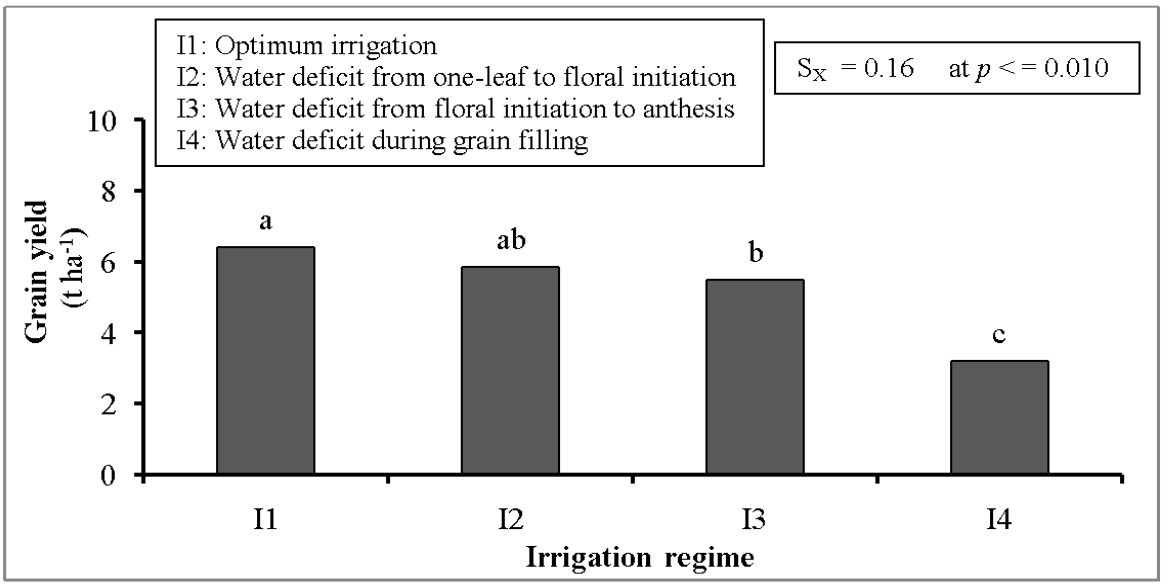

Fig. 6.7. The effect of different irrigation regimes on grain yield of wheat genotypes

The negative effects of water deficit during the anthesis to grain filling stage decreased the number of day to maturity and consequently reproductive duration in the durum and bread wheat genotypes (Table 6.5). These deleterious effects caused reduction in grain weight and 1000- grain weight in the genotypes studied (Table 6.5) which are concurrent with the findings of Sharif-Alhosainy (1998), García Del Moral *et al.* (2003), Saleem (2003) and Kirigwi *et al.* (2004) on durum and bread wheat. Moreover, other researchers (Donalson 1996; Nazeri 2005) have reported that water deficit after anthesis stage decreased grain filling, grain weight and crop production. Therefore, it is reasonable to suggest that a severe reduction in grain yield under the I4 treatment is associated with a decrease in maturity duration and also some of the yield components such as grain weight spike^{-1} and 1000- grain weight.

Table 6.5 Response of grain yield (GY), no. spike m^{-2} (SPKN), no. grain $spike^{-1}$ (GN), 1000- grain weight (TGW), harvest index (HI), plant height (PLH), days to maturity (DMA) and maturity duration (MD) under different irrigation

Traits	GY (tha^{-1})	SPKN	GN	TGW (gr)	HI (%)	PLH (cm)	DMA	MD
Irrigation regime								
I1	6.41 a	432 a	52 a	44.5 b	40.2 a	85.7 a	156a	38 b
I2	5.83 b	398 b	52 a	49.9 a	40.5 a	75.2 c	156a	44 a
I3	5.47 b	304 d	46 b	46.2ab	37.1 a	82.1 b	154a	37 b
I4	3.19 c	362 c	50 a	31.9 c	22.7 b	82.3 b	149a	32 c
LSD	0.429	29.17	2.64	4.64	10.43	1.89	4.21	4.34
Sx	0.052	3.53	0.319	0.561	2.32	0.23	0.51	0.52

Column sharing the same letters indicates no significant differences at $P < 0.01$

Figure 6.8 and Table 6.6 shows the different values for biological and grain yield in the various durum and bread wheat genotypes. The bread wheat cultivar (G3) produced the highest grain yield (5.6 t ha^{-1}) compared to the durum wheat genotypes under the irrigation treatments, although there was no significant difference between the G3 and G2 genotypes. Genotype G4, which registered the lowest value (4.8 t ha^{-1}), did not show a significant difference with the G1 and G5 genotypes. With regard to biological yield (BY), apart from the G1and G3 genotypes that exhibited the highest yield, there were no significant differences among all the other genotypes studied.

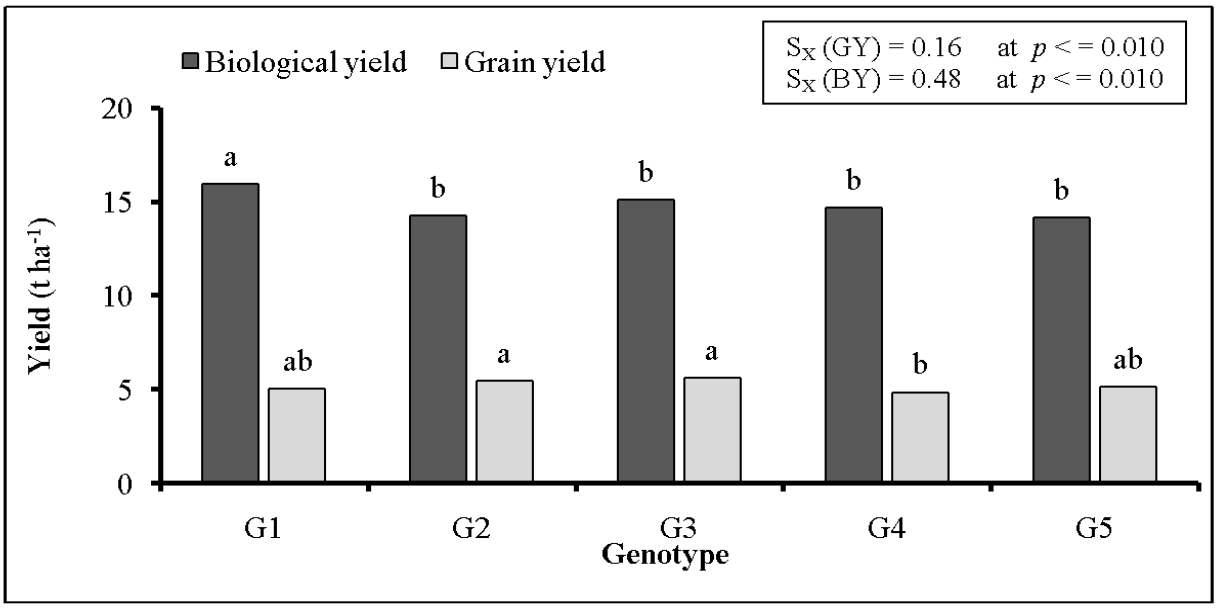

Fig. 6.8. Biological and grain yield in different durum and bread wheat genotypes

Regarding to the interaction effects of the factors studied, the results revealed that the maximum grain yield was produced under optimum irrigation and early water limitation (I2) by the G2 (durum wheat) genotype (Fig. 6.9). However, when the irrigation was reduced during the floral initiation to anthesis stage (I3) and also at the anthesis to grain filling (I4), the Chamran bread wheat cultivar (G3) exhibited the highest grain yield amongst the genotypes. Water limitation at terminal growth stages (I4) decreased grain yield remarkably. The grain yield reduction for the G2 genotype under I4 irrigation treatment was 46% in comparison to the optimum irrigation. According to Blum (1998), identification of high yield potential varieties under optimum moisture and water deficit conditions (slow stressing) has been a principal breeding approach for durum and bread wheat genotypes. The G2 genotype as shown in Fig. 6.9 produced the maximum grain yield under optimum irrigation and water deficit conditions amongst all the other durum wheat genotypes and consequently, may be a suitable genotype under drought stress conditions.

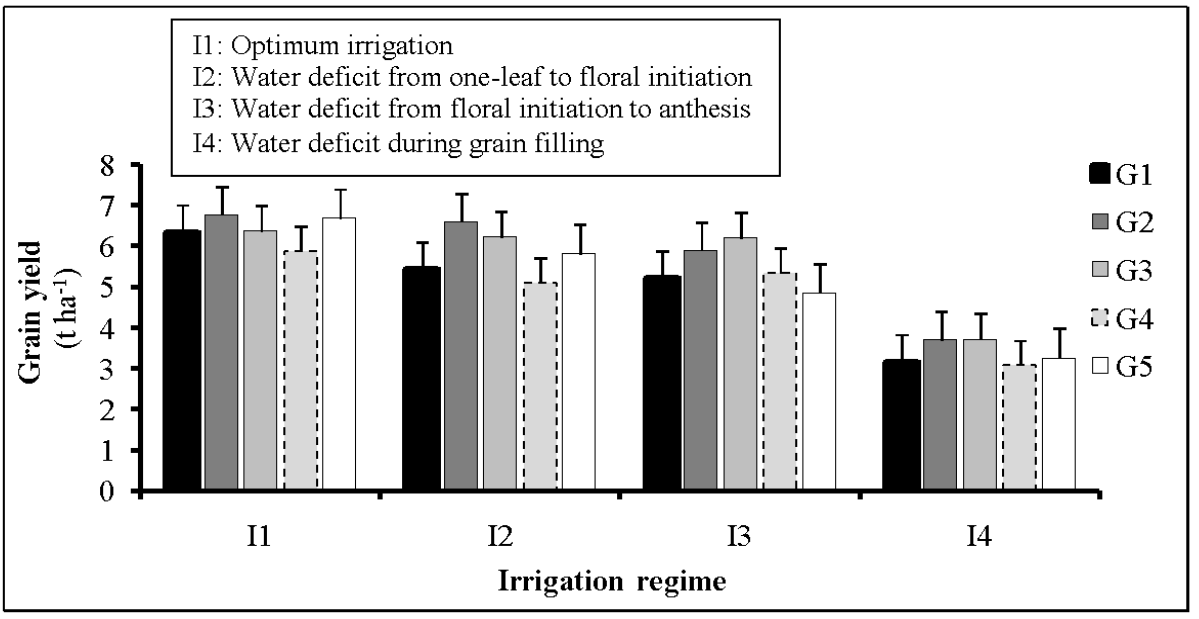

Fig. 6.9 Interaction effect of irrigation regime and genotype on the grain yield in wheat genotypes. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

6.3.14 Effect of Water Deficit and Genotype on Harvest Index

The harvest index (HI) is the proportion of grain yield to biological yield and it shows the ability of the plants to translocate phothosyntetates to grains. Table 6.5 shows that the lowest HI was produced under the I4 treatment. However, there was no significant difference among all the other treatments. There was no significant difference between the optimum irrigation and water limitation at the one-leaf to anthesis stage for this trait. There was a severe reduction of about 44 % of HI in the I4 treatment, compared to the other treatments. The significant reduction in the grain yield under the I4 treatment probably caused a decrease in the HI under I4 in comparison to the other treatments (Fig. 6.7 and Table 6.5). The increase of the HI in the I2 treatment was related to the decreasing biological yield under water deficit conditions. These results are concurrent with the findings of Dakheel *et al.* (1993) on durum wheat and Giunta *et al.* (1993) on both durum wheat and triticale.

The genotypic effects on the harvest index value indicated that the G2 durum wheat genotype gave the highest harvest index of 37%, although there was no significant difference with the G3 and G5 genotypes. In general, there was a similar trend concerning the harvest index with regard to the number of grain, grain weight and 1000-grain weight for genotype effects (Table 6.6).

Table 6.6 Response of biological yield (BY), grain yield (GY), no. spike m^{-2} (SPKN), no. grain $spike^{-1}$ (GN), 1000-grain weight (TGW), harvest index (HI), plant height (PLH) and day to maturity (DMA) in different durum and bread wheat genotypes

Treatment	BY (th^{-1})	GY (th^{-1})	SPKN	GN	TGW (g)	HI (%)	PLH (cm)	DMA
Genotype								
G1	15.9 a	5.1 c	372 b	41 c	40.9 c	31.7 c	80 bc	155ab
G2	14.3 b	5.5 ab	333 c	61 a	46.8 a	37.6 a	81abc	156 a
G3	15.1ab	5.6 a	450 a	50 b	38.6 d	37.1 a	83 a	152 bc
G4	14.6 b	4.9 c	327 c	51 b	43.9 b	33.6 bc	82 ab	151 c
G5	14.2 b	5.2 bc	388 b	49 b	45.3 ab	35.6 ab	79 c	152 bc
LSD	1.06	0.367	24.6	3.38	1.67	2.46	2.48	3.10
Sx	0.27	0.093	3.78	0.52	0.25	0.62	0.38	0.46

Column sharing the same letters indicates no significant differences at $p < 0.01$

6.3.15 Effect of Water Deficit and Genotype on Number of Spike

Figure 6.10 shows that water deficit conditions during the different growth and developmental stages decreased the number of spike m^{-2}. Water limitation caused a decrease spike m^{-2} by 8%, 30% and 16% in the I2, I3 and I4 treatments, respectively, compared to the I1 (optimum irrigation). This shows that the highest negative effect of water limitation was observed during the floral initiation and anthesis stage (I3), whereas the effect of water deficit at the early (I2) and late (I4) growth and developmental stages exhibited lower reduction in comparison to the I3 treatment.

Other researchers also reported similar results on wheat and triticale (Robertson and Giunta 1994; Moustafa *et al.* 1996; Nazeri 2005).

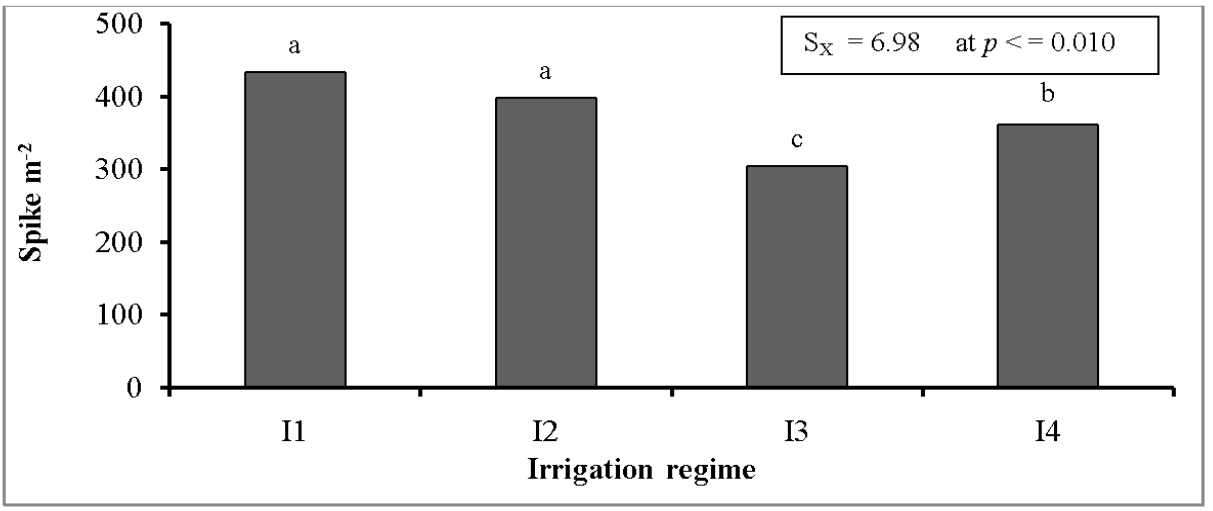

Fig. 6.10. The effect of different irrigation regimes on spike number of wheat genotypes

Water limitation can cause severe competition between the different plant organs for photosynthesis assimilates during the stem elongation (Simane *et al.* 1993; Richards *et al.* 2001 and Kirigwi *et al.* 2004). Therefore, spikes per unit area as the effective factor due to drought stress reduced under reproductive phase (Fig. 6.10 and Table 6.5).

With regard to genotype effects, the Chamran cultivar (bread wheat) exhibited, the highest spike m^{-2} (450) compared to the other durum wheat genotypes. Mossad *et al.* (1995) suggested that amongst the genotypes studied, bread wheat genotypes indicated higher spike m^{-2} compared to durum genotypes. However, except for the G3 genotype, there was no significant difference between the G1 and G5 genotypes and G2 and G4 genotypes (Table 6.6).

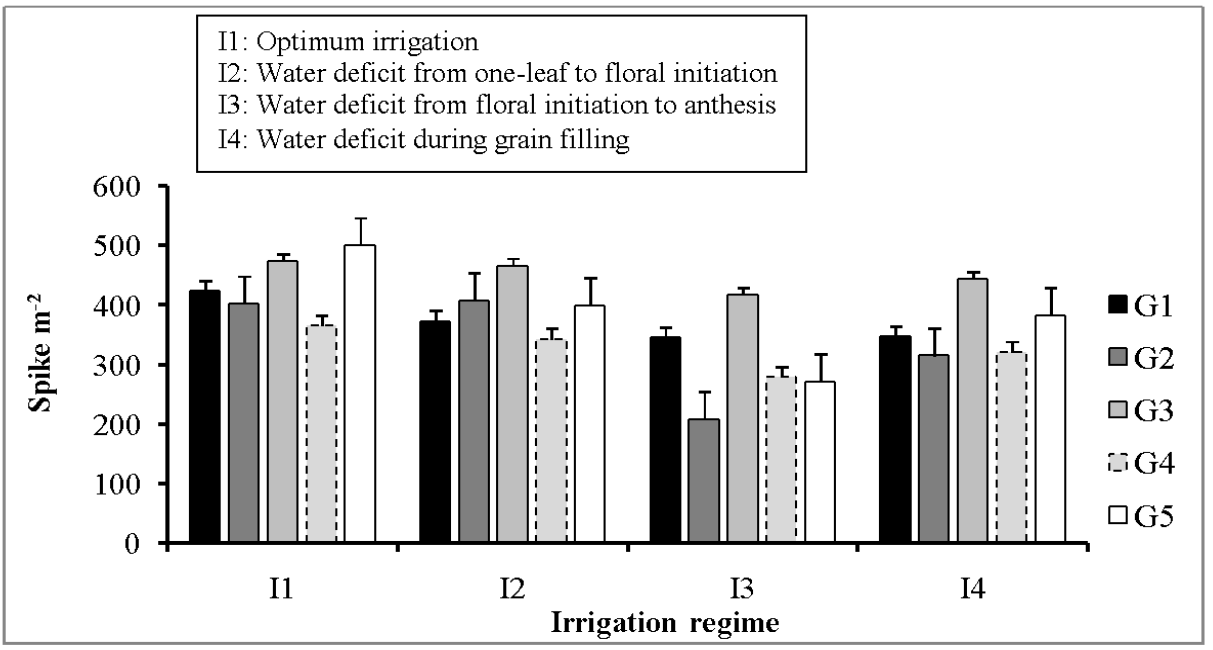

Fig. 6.11. Interaction effect of water deficit and genotype on number of spik in wheat genotypes. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

As shown in Fig. 6.11, except in G5 genotype, which showed the spikes m^{-2} (500) under optimum irrigation treatment, the G3 Chamran bread wheat genotype exhibited the highest number of spikes for all the other water limitation regimes. In addition to this, the highest negative interaction effect for water deficit and genotype was observed in the I3 (water limitation at floral initiation to anthesis) treatment for the G2 genotype. It decreased by 59% compared to the I1G5 treatment.

6.3.16 Effect of Water Deficit and Genotype on Grain Number

The number of the grains per spike (GN) is an important grain yield component. It has been reported that high yield in the new bread and durum wheat varieties are associated with the increasing number of grain per spike or unit area (Calderini *et al.* 1999). The results of the present study shows that there was no significant difference within optimum irrigation (I1), I2 and I4 deficit water treatments for the number of

grains per spike, the exception being the I3 treatment, which yielded the lowest number for this important yield component. The highest number of grains was observed in under water deficit conditions at one-leaf to floral initiation stage (I2) whereas the lowest was seen in the I3 treatment (Table 6.5). This suggests clearly that the floral initiation to anthesis stage (I3) was the most susceptible period for the grains number under water-limited condition, which confirmed the findings of Moustafa (1996) and Ghodsi (2004). They also noted that the number of grains spike^{-1} is determined during the floral initiation to anthesis. As a result, this stage period can be considered as the most crucial growth and developmental stage for the final grain yield.

With regard to genotype effects, Table 6.6 shows that the maximum and minimum number of grain spike^{-1} belonged to the G2 and G1 genotypes under different irrigation treatments. It seems the lower spike m^{-2} in the G2 genotype has been compensated with increasing grain spike^{-1} (Table 6.6) compared to all the studied genotypes. In addition, there were no significant differences among the G3, G4 and G5 genotypes. The results also showed that the difference between the highest (G2) and lowest (G1) genotypes in the grain numbers was more than 30 % (Table 6.6).

6.3.17 Effect of Water Deficit and Genotype on Grain Weight

Although the grain spike^{-1} has a predominant importance over grain weight with regard to grain yield, grain weight is well documented to be a major yield component determining final yield in Mediterranean environments (García Del Moral *et al.* 2003; Peltonen-Sainio *et al.* 2007).

As shown in Table 6.5 water limitation during the anthesis and grain filling stage decreased the grain weight by about 36% compared to the control and other water deficit conditions. Consequently, the most susceptible growth and developmental stage

with regard to grain weight is the anthesis and grain filling stage. Some researchers reported that water limitation during grain filling significantly decreased the 1000 - grain weight although there were no significant effects at the early growth stages (Slafer *et al.* 2001; Martyniak 2002; Nazeri 2005). With regard to the increase in the thousand grain weight at the early water deficit condition (I2) compared to those under optimum irrigation (I1), it may be a form of compensation for the spike reduction under water deficit condition. The result was in agreement with the findings of Robertson and Giunta (1994) and Ghodsi (2004) on bread wheat.

The effect of different genotypes on the 1000-grain weight showed that the highest and lowest weight was shown by the G2 and G3 genotypes. In addition to this, there was no significant difference between the G5, G4 and G2 genotypes (Table 6.6). As shown earlier the highest grain yield was observed in the Chamran bread wheat (G3) cultivar and it was closely associated with the maximum spikes m^{-2} (Figs. 6.8 and 6. 11). The severe reduction in the spike number m^{-2} in the G2 (durum wheat) is compensated with an increase in the grain $spike^{-1}$ and also the thousand grain weight (Table 6.6).

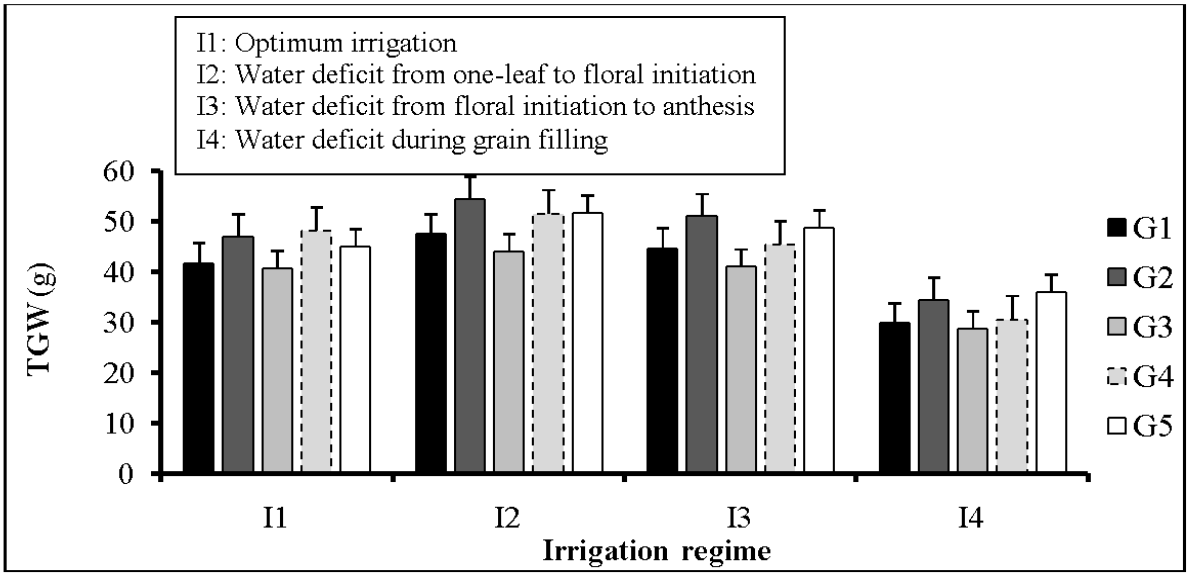

Fig. 6.12. Interaction effect of water deficit and genotype on thousands grain weight (TGW) in wheat genotypes. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

The interaction effects of water deficit and genotype on the 1000-grain weight showed that the G2 and G3 genotypes gave the highest and lowest 1000-grain weight values under optimum and water deficit irrigation regimes, respectively. However, the grain weight of all the genotypes studied decreased with water deficit induced during the reproductive (I3) and the grain filing (I4) period compared to vegetative growth (Fig. 6.12).

6.3.18 Effect of Water Deficit and Genotype on Final Plant Height

As shown in Table 6. 5 the highest and lowest plant heights were measured in the I1 (optimum irrigation) and I2 treatments, respectively. It showed that water limitation during the one-leaf to floral initiation stage caused a significant reduction of about 27% in plant height compared to the plants under optimum irrigation. In addition to this, there was no significant difference between the I3 and I4 treatments for plant height. Richards *et al.* (2001), Saleem (2003) and Ghodsi (2004) have reported that one of the major effects of water stress is to decrease plant height, which also caused a reduction in dry matter accumulation and subsequently grain yield.

With regard to genotypic effects, although the G3 genotype exhibited the highest plant height of 83.5cm under mean irrigation treatments, it was not significantly different between the G4 and G2 genotypes. On the other hand, genotype G5, which showed the lowest plant height of 79.5cm, was not significantly different from the with G1 and G2 genotype (Table 6.6). Plant breeders have tried to select and release intermediate varieties, which has better resistance to lodging under normal irrigation. However these varieties produced less total dry matter although with increasing use of the fertilizers, grain yield has been increased (Calderini *et al.* 1999; Richards *et al.* 2001).

6.3.19 Effect of Water Deficit on Days to Maturity and Maturity Duration

The adaptation strategies of the plants to drought stress includes drought escape, drought avoidance and drought tolerance. Among these strategies, escaping drought involves the completion of the life cycle before the onset of the drought period. Therefore, early maturity has been known as a major drought escaping mechanism, particularly in terminal drought stresses (Levit 1980; Turner *et al.* 2001; Chaves *et al.* 2002). The effect of different water deficit conditions on the number of days to maturity showed that except for the I4 treatment, which need the least number of days to mature, there were no significant differences amongst all the other irrigation treatments. Maturity duration was calculated from the anthesis stage to physiological maturity in the studied genotypes under different water deficit conditions. The highest maturity duration belonged to the I2 treatment compared to optimum irrigation and the I3 and I4 treatments. This showed that water limitation significantly decreased the number of day to maturity and also maturity duration only at the terminal growth and developmental stages (anthesis to grain filling) in the durum and bread wheat genotypes. Accordingly, water limitation in the I4 treatment exhibited early maturity possibly to overcome terminal drought stress (Table 6.5). These results are concurrent with the findings of Simane *et al.* (1993) and Sharif-Alhosainy (1998) who both worked on durum wheat, Kirigwi *et al.* and Ghodsi (2004) on bread wheat and Nazeri (2005) on triticale.

Studies have shown that early maturity trait is a superior characteristic under drought stress conditions. Furthermore, early maturity in the durum wheat genotypes has been known as a drought tolerance parameter in comparison to bread wheat cultivars (Simane *et al.* 1993; Sharif-Alhosainy 1998). The results of the present study on the genotype effects on the number of days to maturity, showed a significant difference between the G2 and G4 genotypes, both of which exhibited the maximum and minimum value for this trait, respectively. However, there was no significant

difference amongst the G4, G3 and G5 genotypes. The Chamran bread wheat cultivar (G3) which has been released as an early maturity cultivar and consequently a drought stress tolerant genotype (Ghodsi 2004), exhibited similar days to maturity as the G4, G3 and G5 durum wheat genotypes (Table 6.6)

6.3.20 Effect of Water Deficit and Genotype on Water Use Efficiency

Effects of irrigation regime, genotype and their interaction were highly significant at p <0.01 for water use efficiency base on biological and grain yield except genotype effect due to biological yield, which was non-significant (Appendix 16).

As shown in Table 6.7, water use efficiency based on biological yield indicated the lowest value (2.69 kg m^{-3}) under optimum conditions and ranged from 2.54 to 3.23 kg m^{-3} under the water deficit treatments. The level of WUE was dependent on the controlled ranges of soil water deficit at different stages. Among water deficit treatments, WUE under I2 treatment (water limitation from one- leaf to floral initiation) showed the highest value based on biological and grain yield while it was shown the lowest value under I4 treatment (water limitation at post anthesis).

As shown in Fig. 6. 13, there were significance differences amongst different irrigation regimes due to water use efficiency based on both grain yield and biological yield. The WUE was ranged 1.32, 1.07, 0.92 and 0.71 kg m^{-3} under I2, I3, I1 and I4 irrigation regime treatments based on grain yield, respectively (Table 6.7). It was also in both the biological and grain yield gradually decreased under water limitation at the vegetative, reproductive and grain filling periods, which was concurred with findings of Al-Kaisi *et al.* (1997), Zhang *et al.* (2003; 2005). They had suggested that timing and the amount of irrigation greatly affects yield and water use efficiency.

In addition, water limitation from one-leaf to floral initiation (I2) stage was improved WUE by 61% (0.5 kg m^{-3}) compared to optimum irrigation (I1) that

confirmed the obtained results by Ghodsi (2004) and Nazeri (2005) on bread wheat and triticale. Moreover, increasing the water use efficiency, in this experiment, under water deficit condition compared to optimum condition was in agreement with findings of other workers (Blum 2005; Zhang *et al.* 2009).

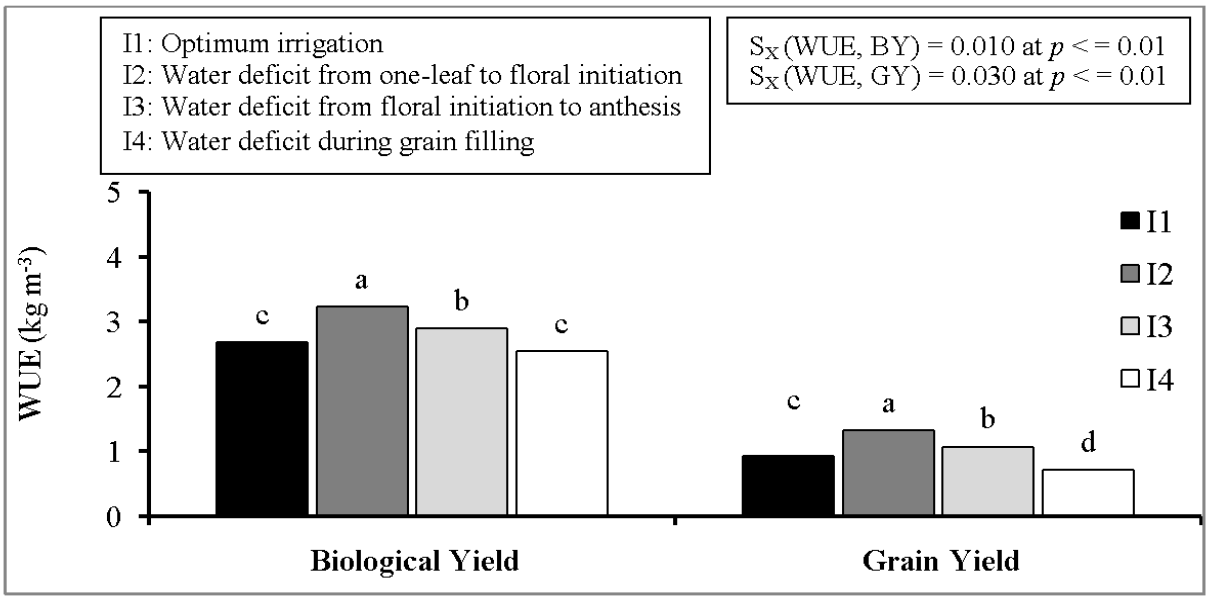

Fig. 6.13. Effect of irrigation regimes on water use efficiency (WUE) based on biological yield (BY) and grain yield (GY) in durum wheat genotypes

Table 6.7 Effect of different irrigation regimes on water use efficiency based on biological yield, grain yield in different durum and bread wheat genotypes

Treatment	Water Use Efficiency (kg m^{-3})	
	Biological yield (BY)	Grain yield (GY)
Irrigation regime		
I1	2.68 c	0.92 c
I2	3.23 a	1.32 a
I3	2.89 b	1.07 b
I4	2.54 c	0.71d
LSD	0.17	0.04
Sx	0.03	0.01
Genotype		
G1	2.76 a	0.87 c
G2	2.76 a	1.06 b
G3	2.80 a	1.22 a
G4	2.76 a	0.89 c
G5	2.72 a	0.8 c
LSD	0.14	0.06
Sx	0.02	0.01

Column sharing the same letters indicates no significant differences at $p < 0.01$

With regard to better extension of the plant roots affected under early season water deficit (Richards 1996), it seems that water limitation under I2 treatment (early season) was improved the water use efficiency by 61% compared to optimum irrigation. A significant correlation was found between stomatal conductance and water use efficiency amongst wheat cultivars under water deficit condition by Zhang *et al.* (2009). Moreover, it had been shown that one of the adaptations of plants for leading to the conservation and efficient use of obtained water under drought condition is the reduction of water loss due to stomatal resistance. Therefore, it is clear that increasing WUE based on grain yield under early season water deficit condition was related to increase in stomatal resistance and reduction of water loss. However, greater extension

of the plant roots under early season water deficit also has been caused better water use efficiency in this stage.

However, WUE for both grain and biological yield decreased under I3 treatment (water limitation from floral initiation to anthesis) compared to I2 but it exhibited higher value in comparison to optimum irrigation. There is a severe competition between vegetative and reproductive plant organs in uptake the soil water during floral initiation to anthesis. Therefore, any water deficit in this period creates a negative effect for those plant organs (Slafer and Whitechurch 2001). In addition, Araus *et al.* (2002) suggested that water absorb by plant during susceptible stages of growth and developmental is one of the important factors for improving the water use efficiency. Therefore, decreasing of the WUE during I3 compared to I2 treatment could be severe competition between vegetative and reproductive organs to imbibe the available water. Increasing the water use efficiency during this period using managing systems can cause a reduction in the negative effects of water deficit on the plant growth and development.

As shown in Fig. 6.13, the lowest WUE was belonged to I4 treatment in both biological and grain yield. It was shown significant differences with optimum and water deficit treatments due to WUE values. However, there was no significant difference between I4 and I1 due to biological yield. Similar irrigation for I1 and I4 treatments until anthesis stage caused maximum dry matter (biological yield) for I4 treatment and consequently similar statistical level compared to optimum irrigation (Table 6.7). Therefore, reduction of biological yield under I4 treatment compared to I1 was related to reduce in grain yield. It has well documented that water use efficiency is a function of available water for plant during grain filling (Richards 1996; Slafer and Araus 1998).

With regard to genotypic differences that affects on WUE in wheat, the results of present study indicated different trend for water use efficiency due to biological and grain yield. There was no significant difference amongst different durum and bread

wheat genotypes due to WUE based on biological yield, whilst G3 and G2 genotypes had shown highest values (based on grain yield) for WUE and significant differences compared to all the other genotypes (Fig. 6.14). The highest WUE were belonged to Chamran bread wheat (G3) and G2 durum wheat with 1.2 and 1.07 kg m^{-3}, whereas it was 0.89, 0.87 and 0.85 in G4, G1 and G5 genotypes, respectively. Priority of G3 and G2 genotypes due to spike harvest index, grain number harvest index and grain yield could be related to grater water use efficiency compared to other studied genotypes (Tables 6.5, 6.9 and 6.11). Several reports have been concerned over genotypic variation among wheat cultivar due to water use efficiency, which were concurred results of current study (Araus *et al.* 2002; Zhang *et al.* 2003 and 2005; Zhang *et al.* 2009).

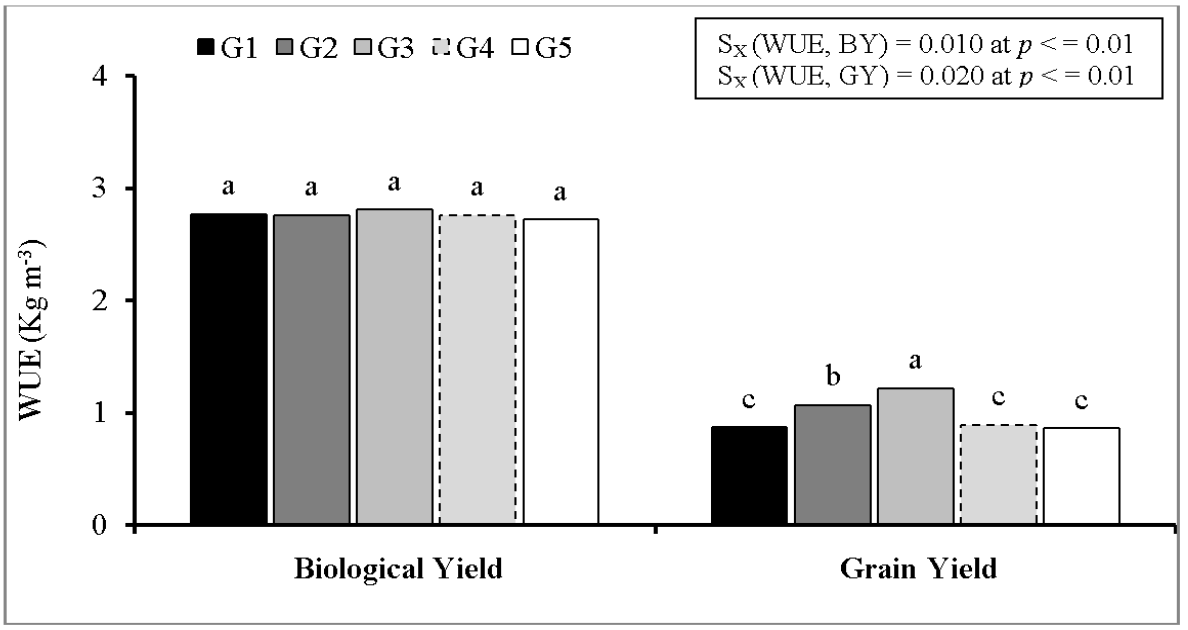

Fig. 6.14. Water use efficiency of different genotypes based on biological yield (BY) and grain yield (GY)

The nteraction effects of irrigation regime and genotype as shown in Fig. 6.15 indicated that the higher WUE has produced under I2 and I3 water deficit treatments compared to I1 and I4. However there were significant differences between genotypes within the irrigation treatments. Generally, maximum WUE were belonged to Chamran

bread wheat (G3) under optimum and water deficit conditions. In addition, G2 durum wheat was achieved to produce second higher values for WUE then G3. Regarding to better RWC in Chamran bread wheat (G3) as a released drought tolerant cultivar, it seems that similar characteristics of G2 and G3, particularly due to water use efficiency can help to introduce this new durum wheat for arid and semi-arid regions.

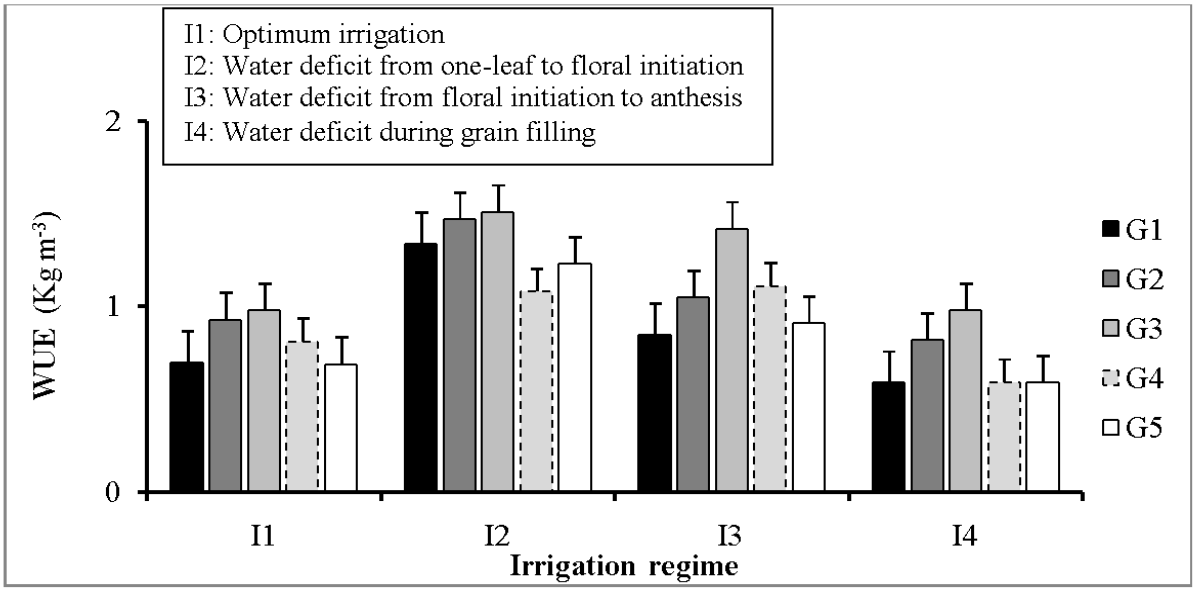

Fig. 6.15. Interaction effects of irrigation regime and genotype on water use efficiency (based on grain yield) in wheat genotypes. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

6.3.21 Drought Tolerance Indices

As shown in table 6.8, the reduction in grain yield from optimum irrigation reached 48.24% over genotypes compared to water deficit at post anthesis (I4). Grain yield (GY) in non-stress condition ranged from 6350 for G1 to 6770 kg ha^{-1} for G2. Significant decreases were found between those genotypes under terminal water deficit conditions (I4) compared to optimum irrigation. The highest value was belonged to G2 (3700 kg ha^{-1}) whereas G4 produced 3080 kg ha^{-1}. Regarding to significant differences between yield potential (I1) and stress yield (I2, I3, and I4), seven quantitative indices of drought tolerance was calculated to detect the most desirable drought tolerance criteria (Table 6.8).

6.3.21.1 Stress Susceptibility Index (SSI)

Table 6.8 shows that the lowest values of the stress susceptibility index were calculated for the G2 and G3 genotypes (0.03) under different water deficit treatments while G5 (0.59) and G1 (0.58) produced the maximum values under I4 water deficit treatment. Higher values of stress susceptibility index (SSI) indicated a higher degree of susceptibility under stress conditions for genotypes and vice versa, which was concurred with findings of Bruckner and Frohberg (1987) and Solomon and Labuschagne (2003). In addition, lower values of the SSI means minimum variations in grain yield of the genotype under non- stress compared to stress conditions that resulted in higher stability in grain yield (Fisher and Morrer 1978). Therefore, this criteria display high yielding genotypes under both stress and non-stress condition. However, G5, which was shown the maximum SSI under water deficit condition, was ranged as second highest yield under optimum irrigation.

6.3.21.2 Stress Tolerance Index (STI)

The higher value of stress tolerance index (STI) means higher tolerance and yield potential for genotype, thus STI is expected to be the most desirable index for drought tolerance (Fernandez 1992; Imamjomah 1999; Farshadfar and Sutka 2003). As shown in Table 6.8, the highest mean of STI were belonged to genotypes G2 (0.89), G3 (0.84), G5 (0.75), G1 (0.71) and G4 (0.71), respectively. Further results indicated that the STI values for G2 and G3 were considerably higher compared to the other studied genotypes under the water treatments (I1, I2, I3, and I4). In addition, those genotypes were also exhibited the maximum grain yield under optimum irrigation and water deficit conditions. Therefore, it seems that the stress tolerance index display better estimate due to grain yield amongst different genotypes under both non-stress and stress conditions.

6.3.21.3 Tolerance Index (TOL)

Tolerance index ranked from 140 to 3420 in G3 and G5under I2 and I4 water deficit conditions.With regard to the TOL which performs the reduction of grain yield in stress condition compared to optimum irrigation. Therefore, the lower values indicate higher tolerance in the studied genotypes to water deficit (Rosielle and Hamblin 1981). As shown in Table 6.8, G3 and G2 which were indicated the lowest values under water deficit conditions (mean stress), thus they are expected to be the most tolerant genotypes to drought stress.

6.3.21.4 Mean productivity (MP) and Geometric Mean Productivity (GMP)

As shown in Table 6.8, the highest MP and GMP (mean) were observed in G2 and G3 genotypes while the lowest values were made for G4 and G1, respectively. Screening of G2 and G3 as the most tolerant genotypes to drought using MP, GMP and STI had shown a similar trend.

6.3.21.5 Yield Reduction Ratio (Yr) and Relative Performance (PR)

Yield reduction ratio ranked from 0.02 to 0.51 in G3 and G2 under I2 and I4 water deficit conations similar to those shown for TOL. However, the most tolerant genotypes based on Yr were G2 and G3 with mean values of 0.14 and 0.15. Yield reduction ratio index had followed from the STI, MP and GMP associated to screening the drought tolerance genotypes (table 6.8). On the other hand, the most tolerant genotypes based on relative performance index (PR) were G3 and G2, which was similar to obtained results for SSI and TOL. The same results were reported by Abo-Elwafa and Bakheit (1999).

Table 6.8 Estimation of stress tolerance attributes from the potential yield and the stress yield data for durum and bread wheat genotypes evaluated using stress susceptible index (SSI), stress tolerance index (STI), tolerance index (TOL), mean productivity (MP), and geometric mean productivity (GMP) and Relative performance (PR) under different irrigation regimes

Genotype	Irrigation regime	GY kg ha^{-1}	SSI	STI	TOL	MP	GMP	Yr	PR
G1	I1	6350							
	I2	5440	0.19	0.84	910	5895	5877	0.14	0.94
	I3	5230	0.22	0.81	1120	5790	5763	0.18	0.96
	I4	3170	0.58	0.49	3180	4760	4487	0.50	0.95
Mean*		**4613**	**0.33**	**0.71**	**1736**	**5481**	**5374**	**0.27**	**0.95**
G2	I1	6770							
	I2	6600	0.03	1.09	170	6685	6684	0.03	1.07
	I3	5900	0.16	0.97	670	6335	5826	0.13	1.01
	I4	3700	0.52	0.61	2970	5235	5005	0.45	1.03
Mean *		**5400**	**0.23**	**0.89**	**1270**	**6085**	**5838**	**0.14**	**1.03**
G3	I1	6370							
	I2	6230	0.03	0.97	140	6300	6299	0.02	1.07
	I3	6200	0.03	0.96	170	6285	6284	0.03	1.13
	I4	3720	0.48	0.58	2650	5045	4868	0.42	1.11
Mean*		**5383**	**0.18**	**0.84**	**986**	**5876**	**5817**	**0.15**	**1.10**
G4	I1	5890							
	I2	5110	0.17	0.73	780	5500	5486	0.13	0.95
	I3	5350	0.12	0.77	740	5620	5613	0.09	1.06
	I4	3080	0.55	0.44	3010	4485	4259	0.48	0.99
Mean *		**4513**	**0.28**	**0.65**	**1510**	**5201**	**5119**	**0.23**	**1**
G5	I1	6680							
	I2	5810	0.17	0.94	870	6245	6230	0.13	0.96
	I3	4850	0.35	0.79	1830	5765	5692	0.27	0.95
	I4	3260	0.59	0.53	3420	4970	4666	0.51	0.92
Mean*		**4640**	**0.37**	**0.75**	**2040**	**5660**	**5529**	**0.30**	**0.94**

Mean* indicates average of the genotype stress tolerance values computed by using different attributes under water deficit conditions

6.3.21.6 Relationship between Drought Tolerant and Susceptible Indices with Grain Yield

To determine the highest desirable drought-resistant genotypes, correlation coefficients among stress yield (YS) and yield potential (Yp), each of the relative performance were estimated and found to be highly significant with positive values (Table 6.9). With regard to estimation of the yield potential (Yp) and stress yield (Ys) which were shown in Table 6.8, correlation analysis revealed a highly significant positive correlation between stress yield (Ys) with stress tolerance index (STI) and mean productivity (MP). Moreover, the relationship between stress yield (Ys) with stress susceptibility index (SSI) and tolerance index (TOL) were shown as a highly significant negative correlation. On the other hand, grain yield under optimum irrigation (Yp) indicated a significant positive correlation with STI and TOL. The highest correlation coefficients were found between stress yield (Ys) with STI (r = 0.98**), Yr (r = - 0.97**), MP (r = 0.97**), TOL (r = - 0.96**) and SSI (r = - 0.95**), respectively. Therefore, the stress yield and STI had shown the strongest relationship to estimate the grain yield under water deficit conditions. In addition, the relationship between yield potential (Yp) and drought indices indicated that STI (r = 0.45*) and TOL (r = 0.09*) had significant correlation whereas there were no significant correlation with all the other parameters. Under most yield trial conditions, the correlation between Ys and Yp is between 0 and 0.5 and genetic variance ratio is lower than one (Farshadfar and Sutka 2003; Nazeri 2005) which was calculated 0.17* for the present study. On the other hand, selection based on tolerance index (TOL) was efficient in improving yield under water deficit conditions, whereas the selected genotypes performed poorly under non-stress environments, which was concurred with findings of Farshadfar and Sutka (2003). Overall, the stress tolerance index (STI) which was exhibited better performance based on drought indices under optimum irrigation and different water

deficit conditions thus can be introduced as the most desirable index for screening drought tolerance genotypes.

Table 6.9 Correlation coefficients among stress yield (YS), yield potential (Yp), stress susceptible index (SSI), stress tolerance index (STI), tolerance index (TOL), mean productivity (MP), and geometric mean productivity (GMP) and Relative performance (P) under different irrigation regimes

Traits	YP	YS	SSI	STI	TOL	MP	GMP	Yr	P
Yp	1	0.17*	0.03	0.45*	0.09*	0.40	-0.08	0.03	-0.11
YS		1	-0.95**	0.98**	-0.96**	0.97**	0.42	-0.97**	0.31
SSI			1	-0.92**	0.99**	-0.90**	-0.45*	0.99**	-0.37
STI				1	-0.89**	0.99**	0.38	-0.92**	0.28
TOL					1	-0.87**	-0.42	0.99**	-035
MP						1	0.37	-0.90**	0.26
GMP							1	-0.45*	0.14
Yr								1	-0.32
P									1

*Correlation is significant at p <0.05 ** Correlation is significant at p <0.01

6.4 CONCLUSIONS

It was observed that the responses of tillering traits in different genotypes varied under optimum and water limitation conditions during the growth and developmental stages. The one-leaf to the floral initiation was the most crucial growth stage for the number of fertile tillers in all the genotypes under water deficit condition. The results also indicated that the number of spikelets per spike, number of potential florets, spike length, spike dry weight, SPC, SHI significantly decreased under water deficit condition during the floral initiation to anthesis stage. Additionally, there were positive relationships between grain yield with number of spikelets per spike, spike length, spike dry weight, day to heading, total and fertile tillers. Overall, the most susceptible growth stage to water deficit was the floral initiation to anthesis stage in durum and bread wheat genotypes. The highest values of grain yield, number of spike m^{-2}, number of grain per spike, plant height and day to maturity were produced under optimum irrigation. However, TGW, HI and maturity duration increased under I2 water deficit condition. It was observed that water deficit at the post anthesis (I4) had caused a highest decrease in the grain yield, TGW, HI, day to maturity and maturity duration. The reduction of the maturity duration at the grain-filling phase reduced dry matter accumulation in the genotypes, which can be the reason for the decreasing TGW. Overall, the severe decrease in the number of spike m^{-2} and number of grain per spike under I3 and TGW at the grain-filling phase contributed to decrease of the grain yield and the HI under the terminal water deficit condition. The highest amount of the water use efficiency was produced under I2 treatment based on biological and grain yield while the lowest value was made under I4 treatment. Water use efficiency under water deficit treatments gradually decreased from I2 (water limitation during one-leaf to floral initiation) to I4 (water limitation during grain. In the other word, terminal water deficit (I4) caused higher decrease in WUE values compared to early season water deficit (I2). In addition,

water limitation from one-leaf to floral initiation (I2) stage was improved the water use efficiency by 61% compared to optimum irrigation. Water use efficiency based on both grain and biological yields decreased under I3 treatment compared to I2, but it was exhibited higher value in comparison to optimum irrigation. Regarding to the post anthesis stage, the lowest water use efficiency was associated with I4 treatment in both biological and grain yields. The reduction in the biological yield under I4 treatment compared to I1 was related to reduce in grain yield. Further, Chamran bread wheat (G3) and G2 durum wheat genotypes exhibited the highest values for total and fertile tillers, number of spikelets, spike length and. In the same vien and based on grain yield, SPC, SHI and WUE glistered highest values for G2 and G3 genotypes.

Amongst the drought tolerant and susceptible indices, used to estimate the highest desirable drought tolerance genotypes, the stress tolerance index (STI) exhibited better performance under optimum irrigation and different water deficit conditions. Therefore, it can be introduced as the most desirable index for screening drought tolerance genotypes. Moreover, the most tolerant genotypes related to different water deficit conditions were Chamran bread wheat (G3) and G2 durum wheat genotypes, which were screened using stress susceptibility index (SSI), stress tolerance index (STI), tolerance index (TOL), mean productivity (MP), geometric mean productivity (GMP), yield reduction ratio (Yr) and relative performance (PR).

CHAPTER 7

APPLICATION OF PHYSIOLOGICAL AND BIOCHEMICAL INDICES FOR SCREENING OF THE DROUGHT TOLERANT DURUM WHEAT GENOTYPES

7.1 INTRODUCTION

Drought is one of the major limiting factors to plant productivity worldwide which influences almost all aspects of plant biology (Romo *et al.* 2001; Pan *et al.* 2002). Despite many decades of research, drought continues to challenge agricultural scientists in general and to plant breeders in particular, due to the unpredictability of its occurrence, severity, timing and duration and the interaction of drought with other abiotic stresses (Ceccarelli and Grando 1996). An understanding of the genetic and physiological bases of drought tolerance would facilitate the development of improved crop management and breeding techniques and lead to improved yield in unfavorable environments (Rekika *et al.* 1998; Nachit *et al.* 2000).

According to Beltrano *et al.* (2006), plants that are able to maintain high levels of relative water content (RWC) under water deficit conditions should be affected less by stress and be able to maintain more normal growth and yield. The findings of several researchers working on durum wheat genotypes revealed that with decreasing of RWC in the leaves under water deficit conditions, the water balance of the plants were disrupted (Bajji *et al.* 2001; Molnár *et al.* 2004; Dulai *et al.* 2006). It also resulted in a fast and considerable stomatal closure and ultimately a decreased rate of net photosynthetic CO_2 fixation.

Many workers have reported that canopy temperature depression (CTD) is a superior indicator of a genotype's physiological suitability in drought tolerance (Pinter *et al.* 1990; Amani *et al.* 1996; Fischer *et al.* 1998; Rashid *et al.* 1999; Reynolds *et al.* 2001; Ayeneh *et al.* 2002). Hence, it has been used in many practical evaluation of plant response to water deficit. Recently, Balota *et al.* (2007) reported that CTD has been used to estimate crop yield and to rank genotypes for tolerance to drought. Previous reports by Blum *et al.* (1982) have shown that canopy temperature differences among

various wheat and triticale cultivars were lowest and highest under favorable and water deficit conditions, respectively. Munjal and Rena (2003) have reported that cool canopy during grain filling period in wheat is an important physiological principle for high temperature stress tolerance. In addition to this canopies with higher water content are indicative of genotypes with higher biomass resulting from larger rates of carbon fixation associated with greater stomata conductance and therefore, cooler canopies (Babar *et al.* 2006). Furthermore, the results of Siddique *et al.* (2000) showed that drought stress significantly decreased the RWC, which had pronounced effects on the photosynthetic rate. The findings of Fischer *et al.* (1998) have shown that wheat genotypes growing under a cooler canopy and under irrigated conditions have higher grain yields. Findings of Bahar *et al.* (2008) related to CTD revealed that that durum wheat was cooler than bread wheat in high temperature conditions. In addition, CTD was positively correlated with grain yield, spike yield, and grain numbers per spike. Overall, CTD has played an important role to search physiological basis of grain yield of wheat, and CTD can successfully use as a selection criterion in breeding programs.

It is well documented that accumulated proline plays a role as a compatible solute in plants, regulating and reducing water loss from the cell under water deficit conditions. It is believed to play an important role in the rehydration of protoplasm and osmotic adjustment in plants. Recently Bayoumi *et al.* (2008) reported that high RWC and proline were identified as beneficial drought tolerance indicators and may be used as selection criteria in wheat breeding programs. Other studies have revealed that proline accumulation is a heritable trait and selection for high proline have been effective in enhancing drought tolerance in plants although it was been suggested that proline is not directly involved in drought resistance and is not essential for improved resistance (Shivkumar *et al.*1998; Silverira *et al.* 2003). Nevertheless, where proline increase does occur, it improves drought resistance (Errabll *et al.* 2006). As the results

of Bayoumi *et al.* (2008) have shown in wheat, the relationship between grain yield and proline accumulation correlated positively under water deficit conditions. It has been suggested that the sharp increase in the proline content might be an adaptation to overcome the stressful conditions and it could supply energy for growth and survival and thereby help the plant to tolerate stress (Sankar *et al.* 2007).

With regard to the important role of photosynthetic pigments, particularly chlorophyll, several studies have shown that a higher chlorophyll content is a desirable characteristic to ensure high photosynthetic carbon dioxide assimilation, particularly during grain filling (Farquhar *et al.* 1989; Young *et al.* 1997; Ort 2001). Findings of Babar *et al.* (2006) have shown positive correlations between chlorophyll concentrations, determined using the handheld portable SPAD (soil plant analysis development) chlorophyll meter, with dry biomass, grain weight per plant and canopy temperature depression in wheat. Besides, the correlation coefficients increased with advancement in growth stage. SPAD chlorophyll meter readings have been shown to be strongly associated with extracted chlorophyll from the plants (Yadava 1986; Dwyer *et al.* 1991).

It is well known that one of the adaptation mechanisms in plants which leads to the conservation and efficient use of water obtained under drought conditions is the reduction of water loss due to stomatal resistance (Turner 1979). The evaporation of water from the surface of a leaf makes it cooler, and the rate of evaporative cooling is affected directly by stomatal conductance. However, photosynthetic metabolism and vascular transport can also affect stomatal conductance. On the other hand, the decrease of the RWC under drought stress conditions disrupts the water balance in plants and causes a rapid reduction in the expansion of the leaves and stomatal conductance (Bajjii *et al.* 2001). The decrease in stomatal conductance is brought about by stomatal closure to reduce the water loss (Cornic 2000; Molnár *et al.* 2004). It has been reported that

there was a significant decrease of the photosynthetic rate and stomatal conductance in wheat under water deficit conditions. The photosynthetic rate dropped from 13 to 1 μmol m^{-2} s^{-1} under water limiting conditions (Fresneau *et al.* 2007; Olszewski *et al.*, 2008). In addition to this, Subrahmanyam *et al.* (2006), Olszewski *et al.* (2008) and Izanloo *et al.* (2008) reported significant differences in photosynthetic rate and stomatal conductance within the wheat genotypes under well water and water stress conditions. It is well known that throughout water deficit, the stomata play an important function in the regulation of transpiration and net photosynthetic CO_2 assimilation (Cornic 1994; Molnár *et al.* 2004). The findings of Izanloo *et al.* (2008) in wheat genotypes indicated a significant negative correlation between stomatal conductance and leaf temperature under water deficit conditions, although there was no significant relationship between them under optimum irrigation conditions.

The present study was carried out to identify appropriate screening tools and quantifiable traits that would facilitate the crop improvement process for drought tolerance using physiological indices. The physiological parameters were also evaluated for screening the drought tolerant durum wheat genotypes under water deficit condition at different growth and developmental stage

7.2 MATERIALS AND METHODS

7.2.1 Field Experimental Setup

In order to study the physiological traits associated with improved drought tolerance for screening the drought tolerant durum wheat genotypes, a field experiment was laid out in the split plot arrangement based on a complete randomized block design, with three replications in Khorasan Agricultural and Natural Resource Research Center at Torogh Research Station, Iran. Four Irrigation regimes were considered as the main-plots, namely: I1, optimum irrigation (well water); I2, irrigation cutting from one-leaf to floral initiation; I3, irrigation cutting from floral initiation to anthesis and prevention of precipitation using a mobile rain shelter; I4, irrigation cutting after anthesis and prevention of precipitation using a mobile rain shelter. Sub-plots were assigned to five wheat genotypes, four durum-promising genotypes (G1, HAI - OU-17/ GREEN - 38; G2, RASCON - 37/ BEJAH - 7; G4, RASCON - 39 / TILO - 1; G5, GARAVITO3 / RASCON37// GREEN8) and a bread wheat cultivar (G3, CHAMRAN), which are summarized in Appendix 6. Besides, other experimental field characteristic and conditions particularly plots sizes, seed density, soil texture, fertilizers used, seed disinfection and weed control were similar to those explained in part 4.2.1.

7.2.2 Measurements

7.2. 2.1 Relative Water Content (RWC)

Sinclair and Ludlow (1985) suggested that the relative water content (RWC) is a reliable measure of the plant's water status. In this study the RWC was determined according to the method of Turner (1981) and Schonfeld *et al.* (1988) at three different growth stages, namely the booting, anthesis and soft dough stages. Ten healthy, and similar-sized flag leaves were harvested early in the morning from each treatment.

Immediately after cutting the base of the leaf lamina, the leaves were sealed within plastic bags and thereafter quickly transferred to the laboratory. Fresh weights were determined within 2 h after excision. Turgid weights were obtained after soaking leaves in distilled water in Petri dishes for 24 h at room temperature (about 20°C), under the low light conditions of the laboratory. After soaking, the leaves were quickly and carefully blotted dry with tissue paper prior to determining the turgid weight. Dry weights were obtained after oven drying the leaf samples for 72 h at 70°C. The RWC was calculated according to the following equation:

$$RWC = (FW - DW) \times 100 / (SW - DW)$$

where FW is the fresh weight, SW the water-saturated weight and DW is the dry weight.

7.2.2.2 Canopy Temperature Depression (CTD)

Canopy Temperature Depression (CTD) is usually expressed as canopy temperature minus air temperature, and this value is higher and a positive number in a well irrigated wheat. Canopy temperature depression was measured with a handheld infrared thermometer (Model THI-500, TASCO, Japan). The data were taken from the same side of each plot at 1m distance from the edge and approximately 50 cm above the canopy. All canopy temperature measurements were made within 2 h of solar noon, and in a south-facing direction, to minimize sun angle effects, as suggested by Turner *et al.* (1986). To avoid the effect of soil temperature on the canopy temperature, the data were taken when the infrared thermometer viewed no soil because of high leaf coverage areas. The canopy temperature measurements were taken at three different growth stages (booting, anthesis and soft dough). In addition, the data for each plot are the means of five sets of readings.

7.2.2.3 Measurement of Proline Contents

Proline was determined in fully expanded leaves according to the method of Pesci and Beffagna (1984). The leaf samples (50 mg) were extracted with 10 ml of sulphosalicylic acid solution (3%) for 1 hour at room temperature and then filtered on Whatman fiberglass paper. A part of the extract (30 mg) was added to 4 ml of ninhydrin and 4 ml of acetic acid and incubated in boiling water for 1 h. After cooling rapidly in ice, 5 ml of toluene was added to the sample and strongly shaken. The absorbance of the toluene phase, containing the colored complex was measured at 515 nm versus a toluene blank. From the absorbance readings obtained the proline content in each sample was calculated by means of a standard calibration curve, using known amounts of proline. Contents of proline were expressed as mg g^{-1} DW.

7.2.2. 4 Leaf Chlorophyll Content

Several workers have reported the strong relationship between readings of the portable chlorophyll meter and leaf chlorophyll content (Yadava 1986; Marquard and Tipton 1987; Markwell *et al.* 1995). In this study, the total chlorophyll content was estimated in intact flag leaves in the field using a handheld portable SPAD-502 chlorophyll meter (Minolta, Tokyo, Japan). It provides a convenient means of assessing relative leaf chlorophyll concentration. At least 10 flag leaf blades were measured to take chlorophyll meter readings from each plot at three different growth stages (booting, anthesis and soft dough). An average of ten measurements taken on different plants in each plot was recorded.

7.2.2.5 Stomatal Conductance

Stomatal conductance was measured on fully expanded flag leaves from five plants in each plot. The measurements were taken at the anthesis with a porometer (Delta-T AP4, Delta-T Devices Ltd, UK) during the middle of the day. The porometer was calibrated at the start of each measurement and the average reading taken on different plants in each plot was recorded.

7.2.2.6 Leaf Photosynthesis Rate

The photosynthetic rate of fully expanded flag leaves was determined using a LCA-4 portable gas exchange system (Analytical Development Company Ltd, UK) during the middle of the day. The middle part of the leaf was enclosed in a leaf chamber (PLC4) and gas exchange measurements made under saturating light conditions, adjusted to an intensity of 1000 μmol photons m^{-2} s^{-1}. Three replicates from each treatment were measured. All the measurements were made on a leaf area basis and the average of three measurements taken in each plot was recorded.

7.3 RESULTS AND DISCUSSIONS

The results of the ANOVA are shown in Appendix 17. It indicates that the effects of the different irrigation regimes, genotypes and their interaction effects for canopy temperature depression (CTD) and leaf relative water content (RWC) were highly significant (p <0.01) at the booting, anthesis and soft dough stages.

7.3.1 Effect of Water Deficit on Canopy Temperature Depression (CTD)

With advancement in the growth and developmental stages, CTD values decreased under optimum irrigation (I1) and water deficit conditions (I2, I3 and I4) (Fig. 7.1). However, the reduction trend was dissimilar for the different irrigation regimes and different growth and developmental stages. The lowest CTD values were observed in the I4 treatment at the soft dough stage followed by the booting and anthesis stages under I3 water deficit treatment (water limitation from double ridge to anthesis). The highest CTD value was recorded when the plants were under optimum irrigation (I1) for all the developmental growth stages. As shown in Fig. 7.1, the highest and lowest CTD values were seen at the booting and soft dough stages under the I4 treatment, which recorded values of 8.43 ˚C and 1.95 ˚C, respectively. On the other hand, the lowest difference in CTD values observed amongst the different irrigation regimes were seen at anthesis. Furthermore, the I1 and 14 irrigation treatments at booting stage exhibited a similar significant level, which is probably related to their similar irrigation regime up to the anthesis period. Figure 7.1 and Table 7.1 also show a significant gradual decrease in the CTD values at the soft dough stage where values of 4.8 ˚C, 4.1 ˚C, 3.2 ˚C and 1.9 ˚C were recorded under the I1, I2, I3 and I4 water treatments respectively.

Table 7.1 Effects of irrigation regime and genotype on canopy temperature depression (CTD) and leaf relative water content (RWC) in different growth and developmental stages

Treatments	Canopy Temperature Depression (°C)			Relative Water Content (%)		
	Booting	Anthesis	Soft dough	Booting	Anthesis	Soft dough
Irrigation regime						
I1	8.40a	5.90a	4.80a	74.35a	70.02a	61.88a
I2	7.00b	5.40a	4.10b	69.31b	64.98b	60.95ab
I3	4.80c	4.80b	3.20c	58.55c	39.55c	54.05b
I4	7.90a	5.60a	1.90d	73.67a	68.78ab	42.81c
LSD	0.67	0.43	0.54	4.16	4.59	7.05
Sx	0.13	0.08	0.10	0.79	0.87	1.34
Genotype						
G1	6.74bc	5.32bc	2.82c	67.86bc	59.69bc	53.42bc
G2	7.45ab	5.86a	4.53a	73.79a	65.63a	57.25a
G3	6.97abc	5.47abc	3.78b	70.63ab	62.49ab	57.33a
G4	7.61a	5.56ab	3.48b	65.93c	57.88c	55.08ab
G5	6.49c	5.07c	2.96c	66.65c	58.48c	51.53c
LSD	0.67	0.41	0.43	3.79	3.78	2.87
Sx	0.17	0.10	0.11	0.97	0.97	0.74

Column sharing the same letters indicates no significant differences at $p < 0.01$

A decrease in CTD with advancement in the growth and developmental stages under optimum irrigation and water deficit conditions has been reported previously by Siddique *et al.* (2000), Khazaei (2002) and Nazeri (2005) suggested that leaf and canopy temperature increase due to drought stress probably occurred due to an increase in respiration and decrease in transpiration as a result of stomatal closure.

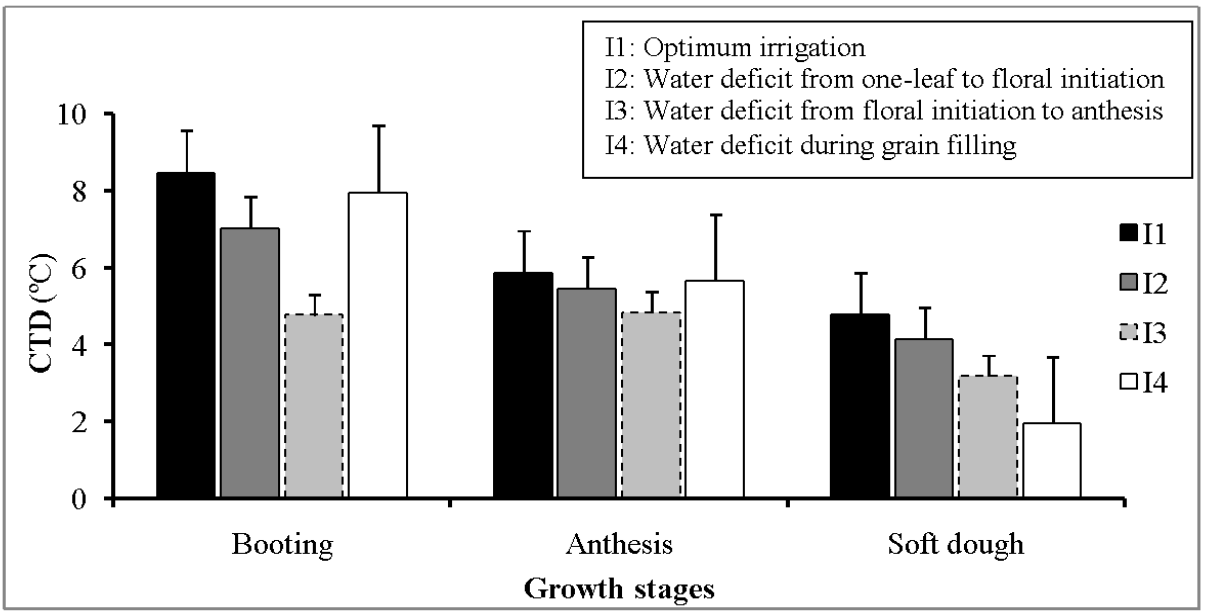

Fig. 7.1. Effect of irrigation regime on canopy temperature depression of durum wheat genotypes at different growth stages. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

7.3.2 Canopy Temperature Depression (CTD) in Different Genotypes

As shown in Fig. 7.2, there was a reduction in CTD in all wheat genotypes, from the booting to the soft dough stages. However, the different genotypes exhibited different temperature at different growth stags, which concurred with the findings of Blum *et al.* (1982) and Nazeri (2005) who reported canopy temperature differences among various wheat and triticale cultivars. The highest CTD (that is cooler canopy temperature) at the booting stage was measured in the G4 durum wheat genotype. However, there was no significant difference between the G4 with G2 and G3 genotypes. In addition, as shown in Fig. 7.2, the biggest difference in canopy temperature amongst the genotypes was seen during the grain filling (soft dough) stage. At the soft dough stage, the durum wheat G2 genotype showed the highest CTD value (4.5 ˚C) compared to other genotypes, followed by Chamran (G3) and G4 durum wheat genotypes. The lowest CTD values belonged to the G5 (2.9˚C) and G1 (2.8˚C) genotypes at the grain filling period. Generally, it can be said that the G2 and G3

genotypes showed better CTD response and consequently canopy temperature compared to other genotypes during the different growth and developmental stages.

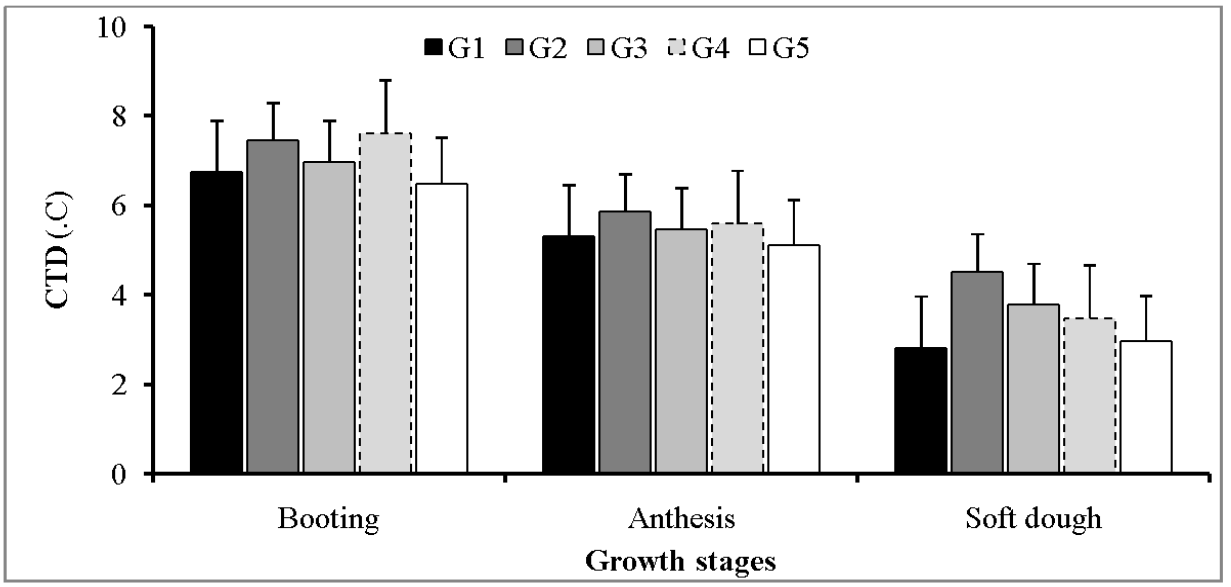

Fig. 7.2. Canopy temperature depression (CTD) of durum wheat genotypes at different growth stages. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

With regard to the importance of canopy temperature during grain filling, the interaction effect of irrigation regime and genotypes on canopy temperature depression at the soft dough stage is shown in Fig. 7.3. It shows that the highest CTD values belonged to the G2 genotype under optimum irrigation (I1) and water deficit conditions (I2, I3 and I4) compared to other genotypes. The Chamran (G3) bread wheat cultivar, which is known to be drought tolerant, exhibited the second highest value for CTD at the I2 and I4 water deficit treatments. The remarkable response shown by the G2 genotype makes it a prime candidate for selection as a desirable drought tolerant genotype under water stress conditions. The results of Balota *et al.* (2007) have strongly suggested that canopy temperature depression could be used to estimate crop yield as well as genotype ranking for drought tolerance. Previous studies by Fischer *et al.* (1998)

had also shown that wheat genotypes with higher grain yield have been demonstrated to have a cooler canopy under irrigated conditions.

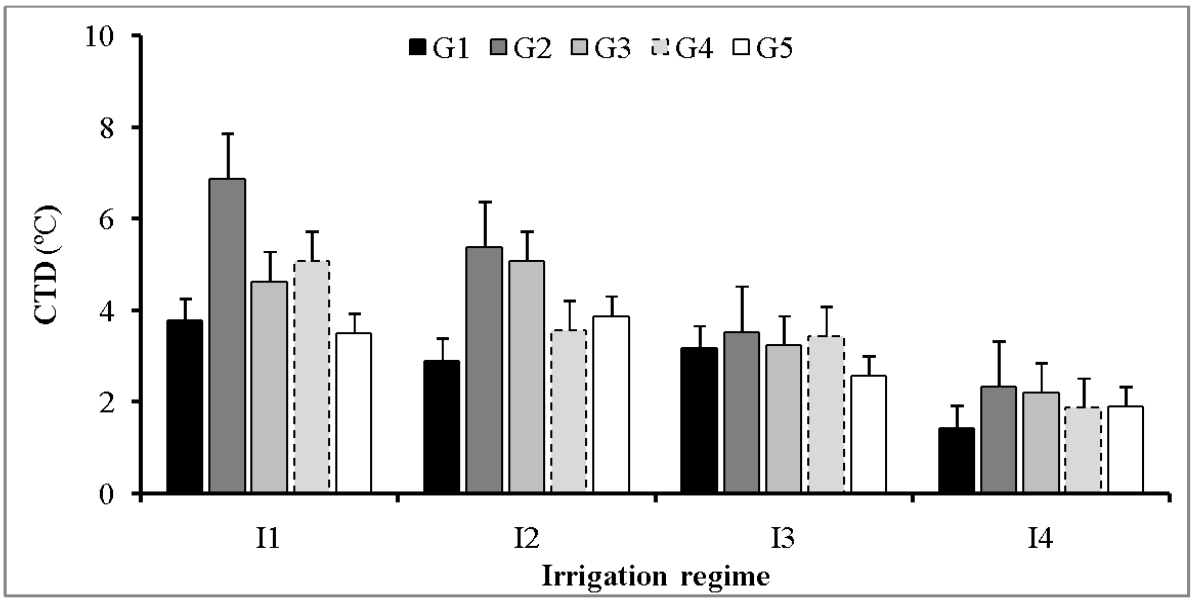

Fig.7.3. Interaction effect of irrigation regime and genotypes on canopy temperature depression (CTD) at soft dough stage. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

7.3.3 Effect of Water Deficit Stress on Leaf Relative Water Content (RWC)

Relative water content is used extensively to determine water status of plants relative to their fully turgid condition. The findings of Beltrano *et al.* (2006) exhibited that under water stress conditions, plants that are able to maintain high levels of RWC would be affected less by the stress and be able to maintain more normal growth and yield. As shown in Fig. 7.1, the highest RWC was made under optimum irrigation (I1) at the booting, anthesis and soft dough stages compared to the water deficit conditions (I2, I3, and I4). The leaf relative water content in optimum irrigation (I1) showed significant differences when compare with the I2 and I3 treatments at the booting and anthesis stages. In addition, there was a significant difference in RWC between optimum irrigation (I1) and the I3 and I4 water deficit treatments at the grain filling

(soft dough) period. The biggest decrease in RWC at the booting and anthesis stages belonged to water limitation at the reproductive phase (I3) while the highest reduction at the soft dough stage was observed under I4 (water limitation from anthesis to late grain filling).

As shown in Figs. 7.4 and 7.1, the decreasing trend in RWC from the booting to the grain filling stage under optimum and water deficit conditions was similar to those observed with CTD. However, there was a significant difference between I1 and 12 treatments for RWC at anthesis. The reduction in RWC under water deficit conditions compared to optimum irrigation in the present study are concurrent with the findings of Khazaei (2002), Ghodsi (2004) and Dulai *et al.* (2006). Furthermore, the reports of Adejare and Umebese (2007) showed that RWC was significantly reduced under water stress treatment at all stages of growth. The results of Siddique *et al.* (2000) also showed that drought stress significantly decrease relative water content, which had a pronounced effect on the photosynthetic rate

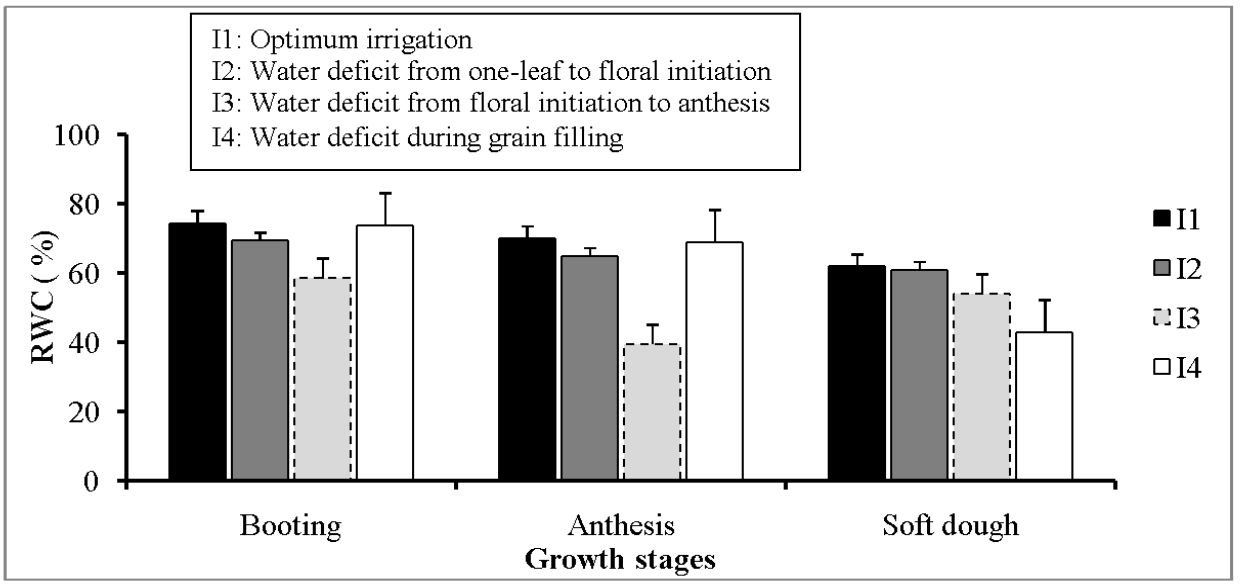

Fig. 7.4. Effect of irrigation regimes on leaf relative water content (RWC) at different growth stages. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

7.3.4 Leaf Relative Water Content (RWC) in Different Genotypes

As was shown in Fig. 7.1, the highest RWC amongst various genotypes belonged to the G2 and G3 genotypes at all growth stages. However, with the advancement of the growth stages, the RWC gradually decreased. The lowest RWC was observed in the G4 genotype at the booting and anthesis stage while the G5 genotype showed the lowest value at the soft dough stage. The results of present study on CTD and RWC in the different genotypes shows that with increasing leaf relative water content the canopy temperature decreased and consequently the CTD increased. This means that the G2 durum wheat genotype, which exhibited the highest RWC at all stages of growth and development, also showed the highest values for CTD (see Fig. 7.2 and Fig. 7.5). Previous studies by Schonfeld *et al.* (1988) had suggested that with increasing water deficit, the RWC decreased. In addition, their findings showed that drought tolerant cultivars have a higher RWC under water deficit conditions.

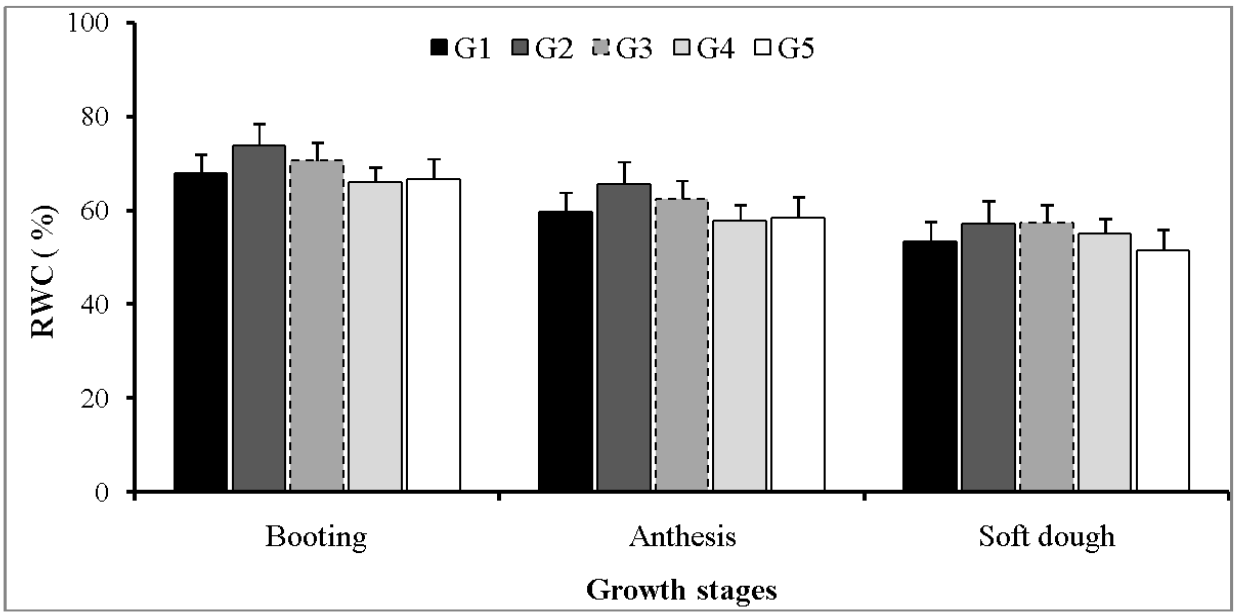

Fig. 7.5. Leaf relative water content (RWC) in different genotypes at growth and developmental stages. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

The findings of Babar *et al.* (2006) also suggests that the canopy with higher water content are indicative of genotypes with higher biomass resulting from larger

rates of carbon fixation associated with greater stomata conductance and therefore, cooler canopies. Bayoumi *et al.* (2008) also suggested that high RWC can be identified as a beneficial drought tolerance indicator and may be used as selection criteria in wheat breeding programs.

7.3.5 Effect of Different Irrigation Regimes on Chlorophyll Content (SPAD)

An analysis of variance in Appendix 18 shows that the irrigation regime showed a significant effect (P <0.05) for chlorophyll content at the booting stage, whilst chlorophyll content in different irrigation regimes, genotype and their interaction were highly significant (p <0.01) during the booting and anthesis stages. There were no significant differences for chlorophyll content at the soft dough stage.

Table 7.2 Effects of irrigation regime and genotype on chlorophyll content (SPAD unit) and proline concentration (mg g^{-1} DW) in different growth and developmental stages

Treatments	Chlorophyll content (SPAD)			Proline concentration
	Booting	Anthesis	Soft dough	(mg g^{-1} DW)
Irrigation regime				
I1	44.77b	45.27b	36.67ab	1.49d
I2	46.51a	46.85b	36.57ab	1.81c
I3	45.95ab	49.21a	40.84a	2.19b
I4	44.31b	44.89b	35.37ab	3.19a
LSD	1.61	2.26	5.15	3.86
Sx	0.46	0.43	1.87	0.73
Genotype				
G1	43.08d	44.38c	37.74a	1.64d
G2	47.61a	48.66a	36.64a	2.66a
G3	44.49cd	45.92bc	37.17a	2.57a
G4	45.13bc	46.18bc	38.28a	1.86c
G5	46.59ab	47.64ab	35.74a	2.13b
LSD	1.668	1.764	2.335	0.209
Sx	0.431	0.456	0.975	0.054

Column sharing the same letters indicates no significant differences at p <0.01

As shown in Table 7.2, there were no considerable differences in chlorophyll content at the booting and anthesis stages under the different irrigation regimes, except from the I3 water deficit treatment at anthesis, which showed the highest value of 49.2, compared to the optimum and the other water deficit conditions. The chlorophyll content values decreased significantly at the grain filling (soft dough) stage under the different irrigation regimes. The lowest value (35 SPAD) was observed in the I4 water deficit treatment at this stage. In addition to this, water limitation at the reproductive phase (I3) resulted in increased chlorophyll content at the anthesis and soft dough stages.

7.3.6 Chlorophyll Content in Different Genotypes

Figure 7.6 shows the leaf chlorophyll content in the various genotypes at different growth stages. There were significant differences amongst the various durum and bread wheat genotypes at the booting and anthesis phases but it was not significant at grain filling.

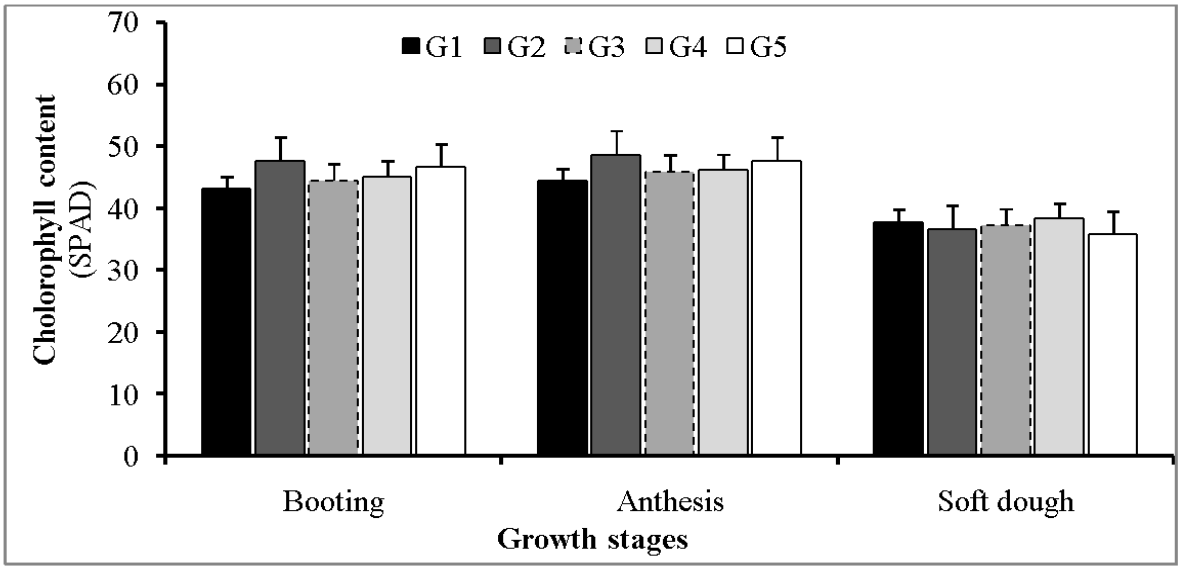

Fig. 7.6. Amounts of leaf chlorophyll content in various genotypes at different growth and developmental stages. Results are shown as mean ± standard error ($p<0.01$), obtained from three replicates

This was probably associated with the advancement in growth and development, where at the grain filling period, the chlorophyll concentrations in the leaves of the different genotypes decreased significantly and consequently the differences between them were minimal. The highest chlorophyll values were determined in the G2 (47 to 48), G5 (46 to 47) and G3 (44 to 45) genotypes at the booting and anthesis phases while the lowest chlorophyll values was observed in the G1genotype (43 to 44).

With regard to the significant interaction effects between irrigation regime and genotypes for chlorophyll content at the anthesis, as shown in Appendix 18 , the highest and lowest amount of leaf chlorophyll content were observed in the G5 and G1 durum wheat genotypes under the optimum irrigation (Fig. 7.7).

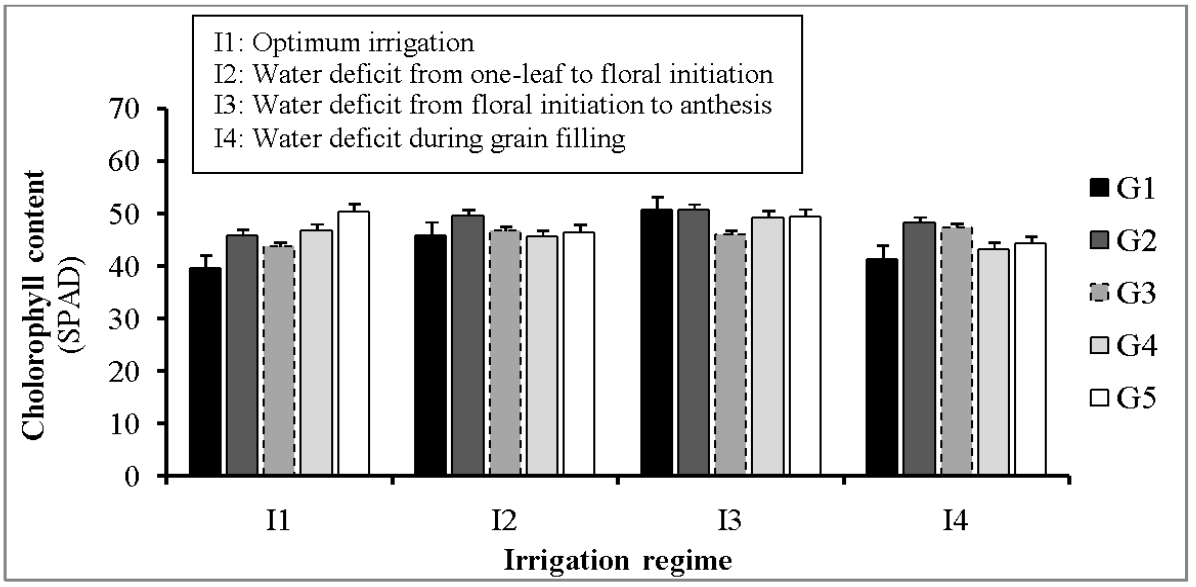

Fig. 7.7. Interaction effect of irrigation regime and genotypes on leaves chlorophyll content at anthesis stage. Results are shown as mean ± standard error ($p<0.01$), obtained from three replicates

Water limitation under I2 (two-leaf to double ridge) and I3 (double ridge to anthesis) treatments increased the amount of the leaf chlorophyll content in different wheat genotypes. The G2 and G3 genotypes recorded the highest chlorophyll content under I2 irrigation while G2 and G1 showed higher values under I3 water deficit

conditions. At the grain-filling period (I4), the G2 and G3 genotypes exhibited the highest chlorophyll content compared to all the other genotypes studied (Fig. 7.7).

Several studies have shown that high chlorophyll content is a desirable characteristic for photosynthesis at high irradiation levels during grain filling (Farquhar *et al.* 1989; Young *et al.* 1997; Ort 2001; Khazaei 2002). From this, it can be inferred that the G2 durum wheat genotype and the G3 Chamran bread wheat cultivar, are suitable and desirable genotypes due to their drought tolerance under laboratory osmotic stress conditions and field experiments However, these results are not in agreement with the findings of Havaux and Tardy (1999) who showed that low chlorophyll content could play a vital function in leaf temperature regulation for barley. On the other hand, Babar *et al.* (2006) reported a positive correlation between chlorophyll concentration and canopy temperature depression in wheat, which are concurrent with the current findings (Figs. 7.3 and 7.7).

7.3.7 Effect of Different Irrigation Regimes on Proline Contents

As shown in Appendix 18, effects of irrigation regimes, genotype and their interaction effects on the proline content were highly significant (p <0.01). There were significant differences in the proline content under the different irrigation regimes where water limitation significantly increased proline accumulation.The amount of proline accumulated was dependent on the stage of plant growth, where water deficit increased the proline content in the leaves by 22 %, 47 % and 114 % of control under the I2, I3 and I4 treatments, respectively (Fig. 7.8 and Table 7.2).

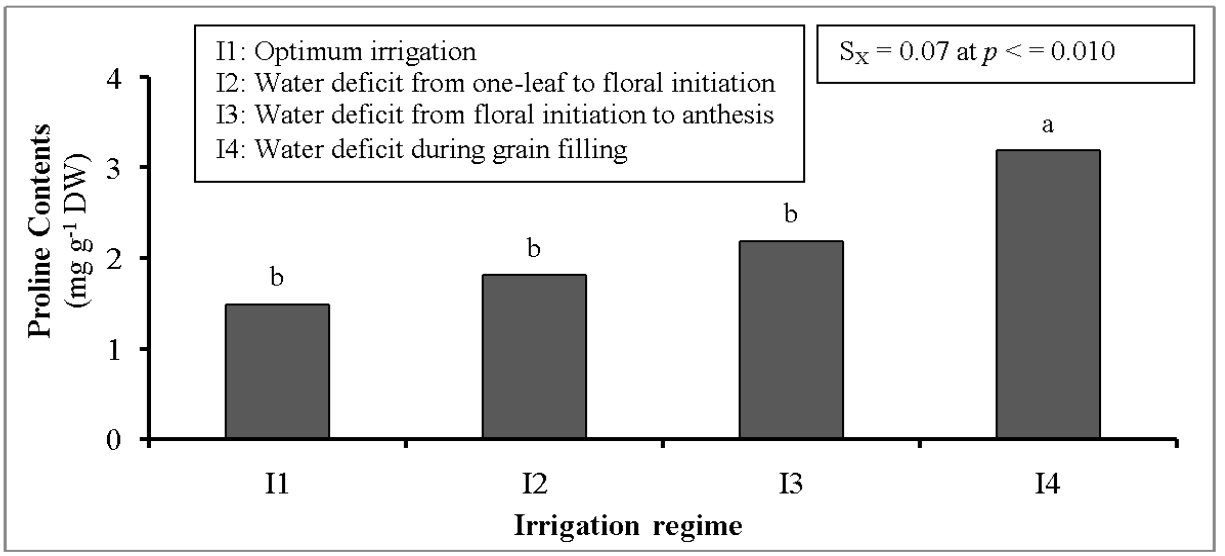

Fig.7.8. Effect of different irrigation regimes on total proline content (mg g^{-1} DW) in the leaves of durum wheat genotypes

7.3.8 Interaction Effect of Water Deficit and Genotype on Proline Contents

As shown in Table 7.2 there were significant differences in proline concentration amongst the genotypes studied. The highest proline content was observed in the G2 and G3 genotypes, whilst the G5, G4 and G1 exhibited lower values, respectively. Bayoumi *et al.* (2008) reported a positive relationship between grain yield and proline accumulation under water deficit conditions in wheat and this suggests that the high proline content in the G2 and G3 genotypes is a positive adaptation for overcoming the stress conditions. Furthermore, Sankar *et al.* (2007) reported that higher proline accumulation in plants could supply energy for growth and survival and thereby help the plant to tolerate stress. Therefore, proline accumulation in plant leaf cells as a compatible solute plays an important role in regulating water loss from the cells under water deficit and osmotic stress conditions (Bayoumi *et al.* 2008). It is therefore reasonable to suggest that the selection of new drought tolerance genotypes based on high proline content can be effective in enhancing drought tolerance in plants (Shivkumar *et al.* 1998; Silverira *et al.* 2003).

The interaction effect between irrigation regime and genotype, as shown in Fig. 7.9, also showed that proline accumulation increased under water deficit conditions compared to optimum irrigation. The highest proline accumulation values was seen in the G3 (3.95) and G2 (3.77) under I4 water deficit conditions. However the highest proline content values under optimum irrigation conditions was seen in the G5 (1.8) and G1 (1.6) durum wheat genotypes. Besides this, these genotypes also exhibited higher proline values at the vegetative (I2) and reproductive (I3) phases under water deficit condition compared to optimum irrigation.

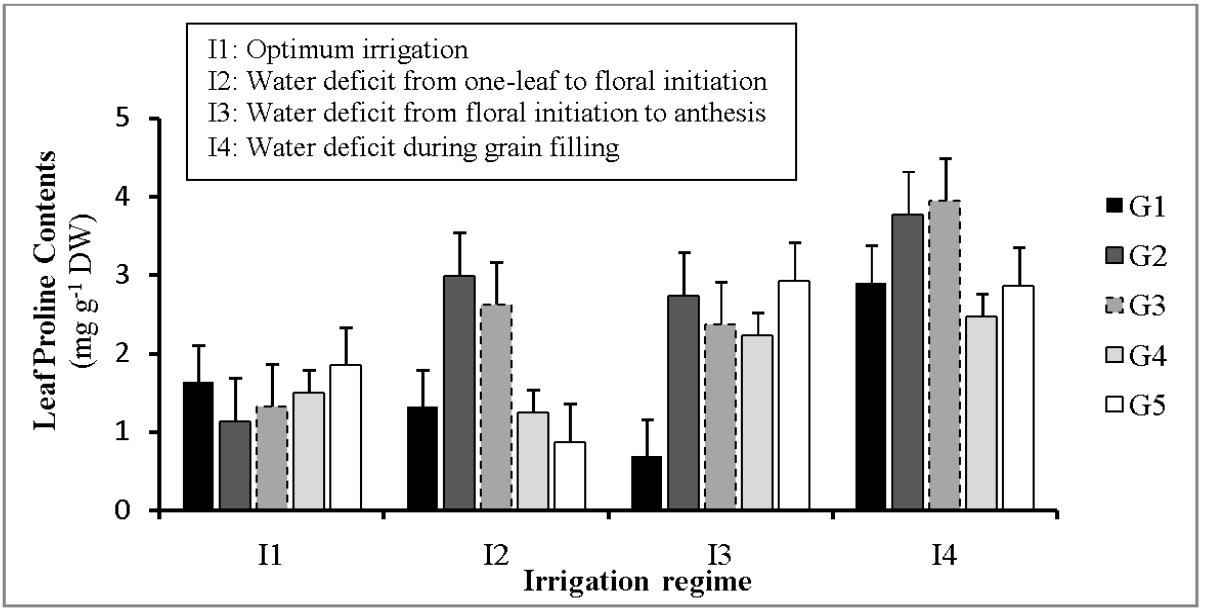

Fig. 7.9 Interaction effects of irrigation regime and genotype on total proline content (mg g-1 DW) in the leaves of different durum and bread wheat genotypes. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

7.3.9 Effect of Different Irrigation Regimes and Genotype on Stomatal Conductance

The effects of the different irrigation regimes and genotype on stomatal conductance and photosynthesis rate were highly significant (P <0.01) in all stages of growth (booting, anthesis and soft dough) except for the effect of genotype on stomatal conductance which exhibited a significant effect (p <0.05) at the booting stage (Appendix 19).

As shown in Figs. 7.10 and 7.11, stomatal conductance decreased with age of the leaves under the different irrigation regimes and various genotypes. The biggest reduction in stomatal conductance were observed under I2, I3 and I3 water deficit treatments at booting, anthesis and soft dough stage, respectively. The biggest decrease due to plant age between the studied genotypes was seen in the G1 and G5 durum wheat genotypes, whereas the G2 and G3 showed the lowest differences amongst the genotypes.

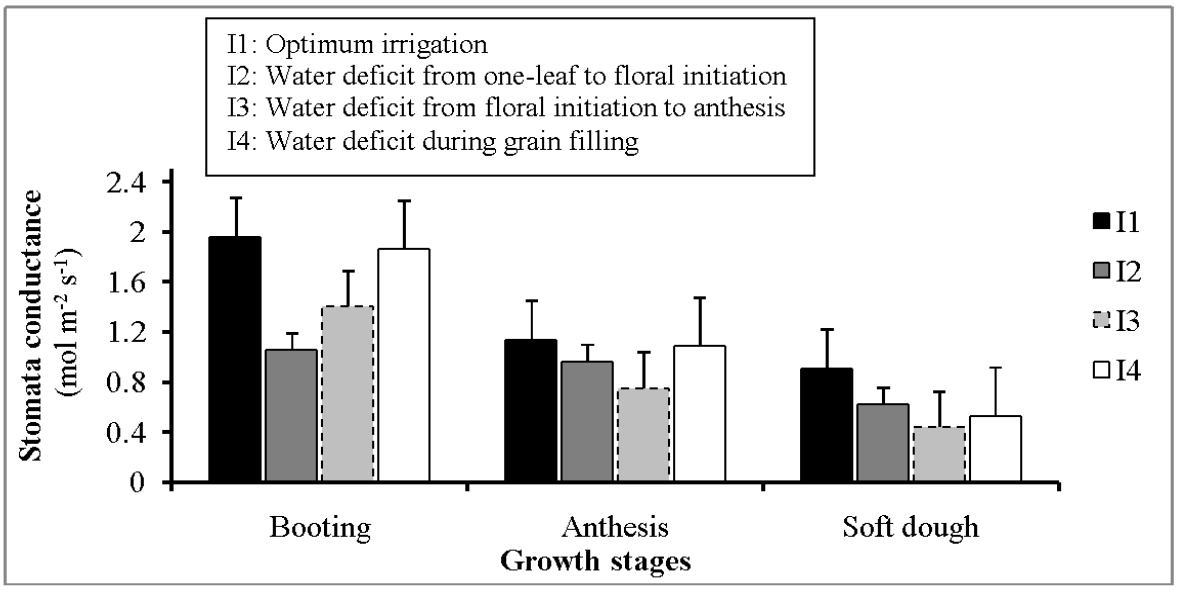

Fig. 7.10. Effect of irrigation regimes on stomatal conductance at different growth stages. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

The maximum stomatal conductance was observed under optimum water conditions for the growth and developmental stages. The highest (1.95 m mol m^{-2} s^{-1}) and lowest (0.44 m mol m^{-2} s^{-1}) stomatal conductance were recorded at the booting stage under optimum irrigation and soft dough stage under I3 water irrigation (water limitation from double ridge to anthesis), respectively (Table 7.3).

Table 7.3 Effects of irrigation regime and genotype on stomatal conductance and photosynthesis rate in different growth and developmental stages

Treatments	Stomatal Conductance (m mol m^{-2} s^{-1})			Photosynthesis Rate (μ molCO2 m^{-2} s^{-1})		
	Booting	Anthesis	Soft dough	Booting	Anthesis	Soft dough
Irrigation regime						
I1	1.95a	1.13a	0.90a	18.10a	13.04ab	10.30a
I2	1.05c	0.96b	0.62b	8.05c	10.43bc	7.87b
I3	1.40b	0.75c	0.44c	10.40b	8.46c	4.78c
I4	1.86a	1.08a	0.532c	17.85a	14.0a	6.14c
LSD	0.16	0.105	0.13	1.68	2.76	1.52
Sx	0.03	0.02	0.02	0.32	0.53	0.29
Genotype						
G1	1.53b	0.63c	0.295c	11.90c	8.34b	4.01b
G2	1.55b	1.29a	0.873a	13.24bc	13.23a	8.93a
G3	1.55b	1.15ab	0.961a	13.31bc	13.04a	9.25a
G4	1.65a	1.05b	0.630b	16.03a	12.90a	8.59a
G5	1.55b	0.78c	0.365c	13.54b	9.89b	5.58b
LSD	0.08	0.19	0.18	1.38	1.93	1.98
Sx	0.03	0.05	0.05	0.36	0.49	0.51

Column sharing the same letters indicates no significant differences at $p < 0.01$

There were genotypic differences in stomatal conductance amongst the various durum and bread wheat genotypes (Fig. 7.11). The G4 durum wheat genotype, exhibited the highest stomatal conductance at the booting stage, whilst, there were no significant

differences amongst all the others genotypes at the same stage. However the results showed that with the advancement of growth and development, the G2 and G3 genotypes exhibited higher values compared to the other genotypes. Conversely, the G1 and G5 genotypes recorded the lowest values for this parameter at the same growth and developmental stages (Table 7.3). This shows that the stomatal conductance values varied greatly among the genotypes studied at the anthesis and soft dough stages compared to booting stage.

The stomatal conductance in the G1 genotype dropped by 59 % and 80 % at the anthesis and soft dough stages, respectively, compared to booting stage. Similarly, for the G5 genotype the reduction was 49 % and 77 % at the same growth stage. However, both the G2 and G3 genotypes showed a lower reduction in stomatal conductance (17- 44 % and 26 -39 %) at the anthesis and soft dough stages.

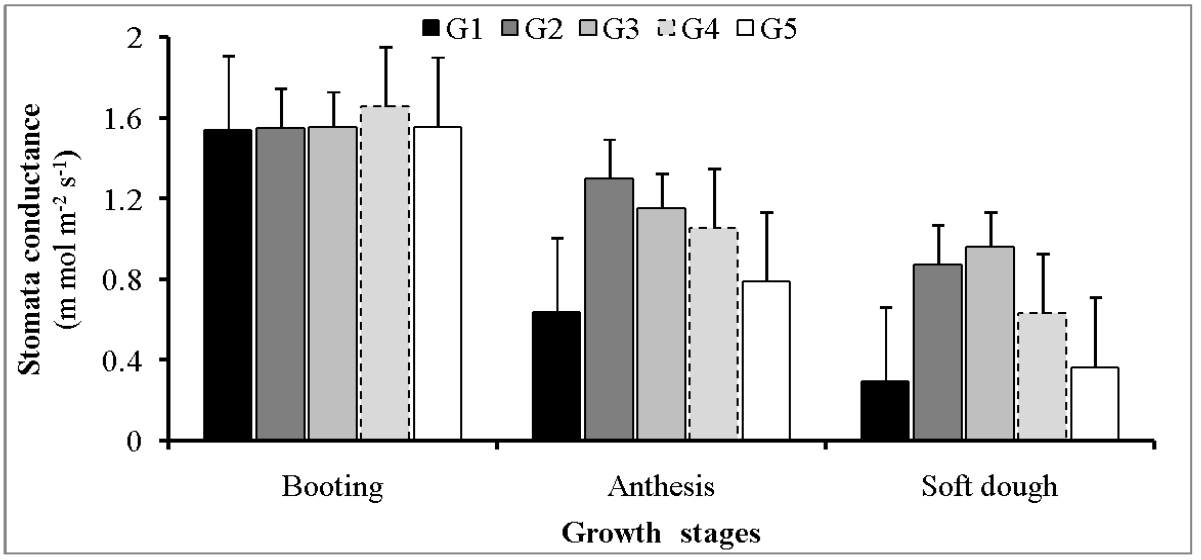

Fig. 7.11. Amounts of stomatal conductance in various genotypes at different growth stages. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

These results are in agreement with those of Cornic (2000) and Molnár *et al.* (2004), who reported that stomatal conductance decreased in the matured leaves of wheat with age increasing as a result of stomatal closure to reduce water loss.

The interaction effect between the irrigation regimes and genotype, as shown in Fig. 7.12, shows that with the imposed water deficit, the stomatal conductance decreased in the G2 and G3 genotypes, but surprisingly showed a little increase in the G1, G4 and G5 genotypes under the I2 water deficit treatment. In addition to this, several researchers has reported significant cultivar differences in stomatal conductance within wheat genotypes under normal and water stress conditions which probably explains the present results (Siddique *et al.* 2000; Subrahmanyam *et al.* 2006; Olszewski *et al.* 2008; Izanloo *et al.* 2008).

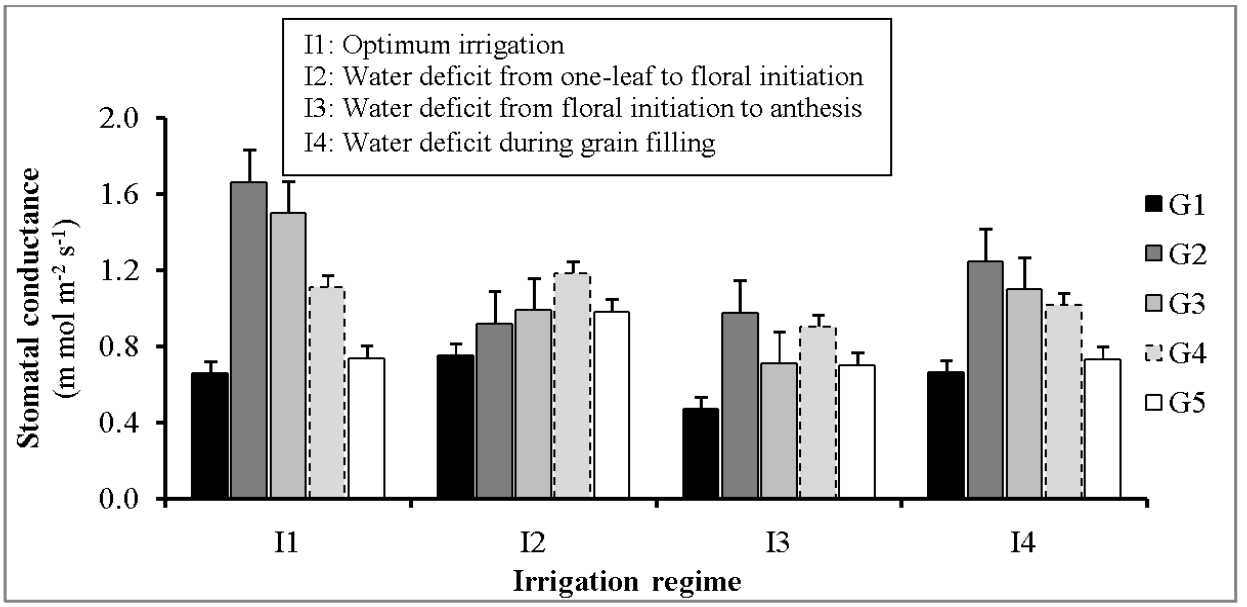

Fig. 7.12. Interaction effect of irrigation regime and genotype on stomatal conductance at anthesis stage in different durum and bread wheat genotypes. Results are shown as mean ± standard error ($p<0.01$), obtained from three replicates

7.3.10 Effect of Different Irrigation Regimes and Genotype on Photosynthetic Rate

As shown in Figs. 7.13 and 7.14, the trend in photosynthetic rate at the different growth and developmental stages was similar to those shown for stomatal conductance (Figs. 7.10 and 7.11). The photosynthetic rate decreased with age of the leaves under the different irrigation regimes and various genotypes. The photosynthetic rate of plants in the I1 treatment dropped by 28 % and 45 % at the anthesis and soft dough stages whilst the reduction for plants under the I4 water deficit treatment was 18% and 65 % at the same growth stages. The lowest photosynthetic rate (4.78µmol CO2 $m^{-2}s^{-1}$) was recorded in the I3 treated plants at the soft dough stage whilst the highest photosynthetic rate of 18.1 µmol CO2 $m^{-2}s^{-1}$ was recorded in the plants under optimum irrigation (I1) at the booting stage.

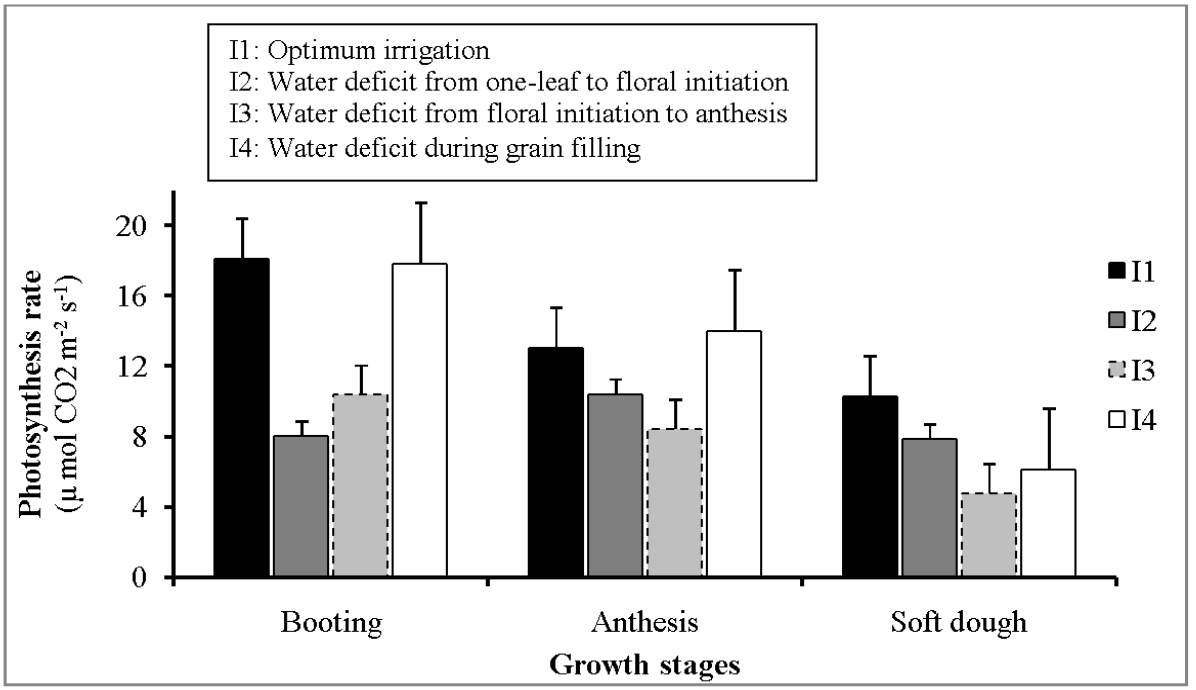

Fig. 7.13. Effect of irrigation regimes on photosynthetic rate at different growth stages. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

The photosynthetic rate of the different genotypes at the various growth and developmental stages are shown in Table 7.3 and Figure 7.14. The values decreased with age of the leaves in the durum and bread wheat genotypes. At the booting stage, the G4 and G1 genotypes showed the highest and lowest photosynthetic rates respectively. However during anthesis the G2 and G3 genotypes exhibited higher photosynthetic rate relative to other genotypes. At the soft dough stage, there was a marked reduction in the photosynthetic rate as compared to the anthesis stage, although, rates between the genotypes were similar to those shown at the anthesis stage. The reduction in photosynthetic rate relative to the age of the plants observed in this study was in agreement with the finding of Siddique *et al.* (2000). Furthermore, several researchers (Subrahmanyam *et al.* (2006), Olszewski *et al.* (2008) and Izanloo *et al.* (2008) who reported genotypic differences in photosynthetic rate among the wheat genotypes under different conditions concurred with the results of the present study.

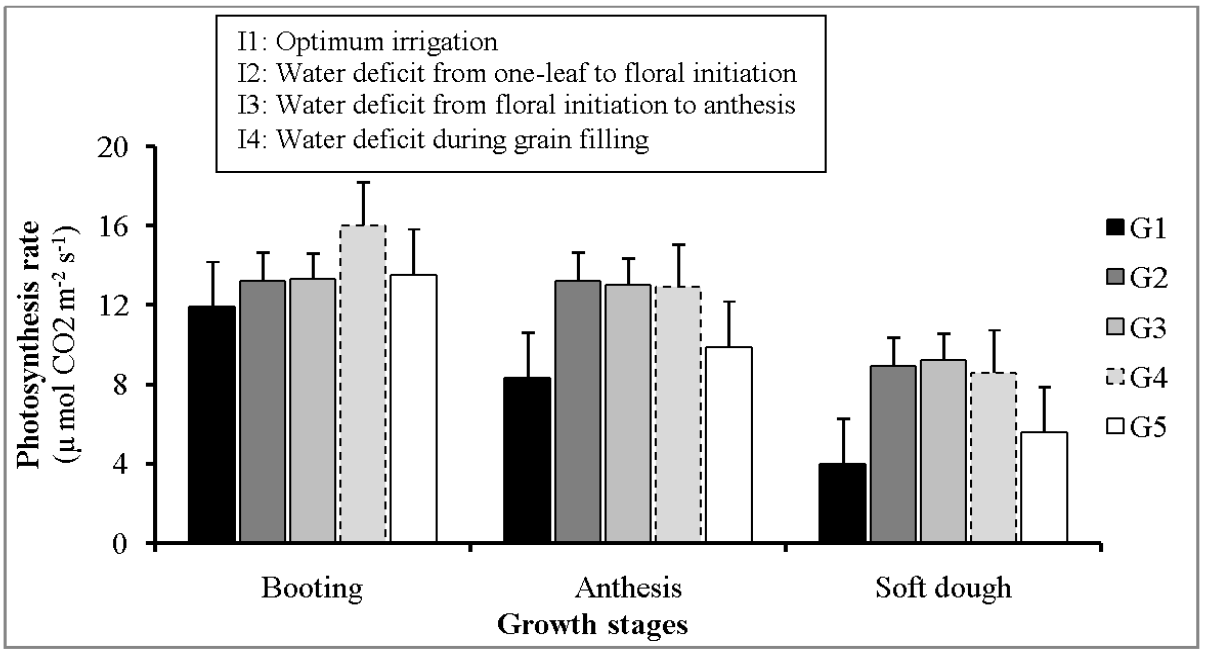

Fig. 7.14. Photosynthetic rate in various genotypes at different growth stages. Results are shown as mean ± standard error (p<0.01), obtained from three replicates

7.4 CONCLUSION

The results showed that with advancement in the growth and developmental stages, the values of RWC, CTD, chlorophyll content, stomatal conductance and photosynthetic rate decreased under both optimum irrigation and water deficit conditions. In addition, water limitation during grain filling significantly decreased RWC, CTD, chlorophyll content, stomatal conductance and photosynthetic rate at the soft dough stage. The results indicated that decrease in RWC under water stress conditions disrupted water balance in the plants and consequently reduced stomatal conductance and photosynthetic rate. With increasing leaf temperature (and a concomitant decrease of CTD), as affected by reduction in RWC, both stomatal conductance and photosynthetic rate decreased. Although with the advancement in growth and development, the RWC, CTD, chlorophyll, stomatal conductance and photosynthetic rate in all genotypes decreased, the degree of reduction varied in the various genotypes studied. The genotypes, G2 and G3 both exhibited the highest RWC, CTD, chlorophyll and proline accumulation, stomatal conductance and photosynthetic rate under water deficit conditions compared to optimum irrigation. From the results, it can be concluded that the G2 durum wheat is a suitable genotype for cultivation under drought conditions, performing better, in several physiological aspects, than the established Chamran bread wheat drought tolerant cultivar and other durum wheat genotypes studied in present experiment.

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSION

8.1 GENERAL DISCUSSION

Water is the largest component in the make-up of plants and serves as the solvent which transports minerals and dissolved carbohydrates throughout the p Therefore, accessibility of water for plant growth is a key factor determining plant distribution in natural ecosystems and is the single most important limiting parameter in agricultural systems. Water stress is a common and wide occurrence in nature that occurs whenever water absorption by the crop is lower than the evaporative demand of the atmosphere. It has been well documented that one of the important challenges facing crop physiologists and agronomists is understanding and overcoming the major abiotic stresses in agriculture, which reduces crop productivity and yield. Consequently, developing more drought tolerant plants with suitable advantages under water stress conditions is a fundamental challenge and important strategy for wheat improvement programs (Siddique *et al.* 2000; Casati and Walbot 2004; Dai and Li 2004; Passioura 2007).

As outlined at the end of chapter 1 the principal objectives of the research programme embodied in this thesis were to analyze how water deficit was related to ecophysiological traits in different wheat genotypes during different growth stages. Further, in order to access a shortcut breeding method for screening of the drought tolerance genotypes durum and bread wheat genotypes, which were screened under laboratory (germination and seedling imposed by osmotic stress) and field conditions were compared. A brief summary of the findings is reported in this chapter. Other significant findings and details have been discussed in the earlier chapters.

Seed germination is considered to be the most critical growth stage under water stress conditions, as it is a requirement for the success of the stand establishment of crop plants. The response of germination traits in the different genotypes changes at the

germination and seedling stages under control and osmotic stress conditions. In the other word, the germination characteristics depend on genetic factors in the plant and on the osmotic stress conditions. The results of present study showed that germination percentage and rate, coleoptiles length, root and shoot length, root and shoot seedling dry weight, root to shoot length ratio, and root to shoot dry weight ratio were highly significantly affected under osmotic stress treatments. In addition to this, the difference in germination percentage and rate in the various durum wheat genotypes studied were highly significant ($p < 0.01$) whilst for coleoptiles length, root length and root dry weight the differences were significant at $p < 0.05$ (Appendix 5).

It was observed that germination percentage, coleoptile, root and shoot length, shoot and seedling dry weight decreased with increasing osmotic stress (Figs. 3. 1, 3.2 and 3.4), whereas root to shoot length ratio and root to shoot dry weight ratio increased (Fig. 3.3). Furthermore the germination rate and root dry weight increased in the -0.3 MPa treatment compared to the control but decreased with increasing severity of the osmotic stress (-0.3 to -0.9 MPa). Correlation studies among the different traits showed that the highest correlation was between seedling dry weight and shoot dry weight. On the other hand, the lowest correlation was between germination rate and root to shoot dry weight.

With regard to drought tolerance, the overall results of the present study also showed that with increasing osmotic stress, the germination stress tolerance index (GSTI) decreased significantly. Hence, the highest and lowest values for GSTI was observed in low (-0.3 MPa) and severe osmotic stress treatments (-0.9 MPa). From these observations it can be inferred that the osmotic stress level of -0.6 MPa can be the germination sensitivity threshold in the durum and bread wheat genotypes studied. Furthermore, a comparison of the GSI and GSTI values from the screening of the tolerant genotypes revealed that the results obtained were considerably similar for both

of the studied indices. The promising durum wheat genotypes RASCON-39/TILO-1 and RASCON-37/ BEJAH-7 were observed as the most tolerant genotypes under low and severe osmotic stress whereas GARAVITO-3/RASCON-37// GREEN-8 and HAI-OU-17/GREEN-38 exhibited the lowest GSTI values under osmotic stress conditions (Chapter 3).

Water deficit reduced growth parameters such as leaf area index, crop growth rate, relative growth rate, net assimilation rate, photosynthetic active radiation interception, radiation use efficiency and consequently accumulation of dry matter compared to optimum irrigation in each of the growth and developmental phases for durum and bread wheat genotypes. From this it can be inferred that, dry matter accumulation, which is the transformation of the light radiation into biomass in plants, is a function of the leaf area index and intercepted photosynthetically active radiation by plant canopy. Significant decrease of the leaf area index and photosynthesis active radiation interception under water deficit conditions, consequently reduced dry matter by 24%, 31%, 39%, 33%, 31% and 26% at the double ridge, terminal spikelets, booting, anthesis, soft dough and physiological maturity stages under I2 (water limitation from one-leaf to floral initiation) water deficit treatment compared to optimum irrigation, respectively (Table 4.1). However, general pattern of cumulative dry matter according to the cumulative growing degree-days and photosynthesis active radiation interception across the growth and developmental cycles indicated an incremental trend under both optimum and deficits irrigation conditions.

Negative effect of the early season water deficit (I2) on decreasing the leaf area index and dry matter were extended until the terminal maturity, even under re-irrigation after the double ridge. Therefore, the rapid leaf area extension at the early growth stage causes better establishment of the plant to prevent the water evaporation from the soil surface that is known as a very important factor to overcome the early-season drought

conditions. On the other hand, the reduction of the leaf area index and shortening in the grain-filling period under I4 (post-anthesis water limitation) treatment had been decreased significantly photosynthesis active radiation interception at the same stage.

Among different durum and bread wheat genotypes, the highest values for leaf area index were belonged to G2 (4.45), G3 (4.39), G1 (4.08), G5 (3.88) and G4 (43.86) at the anthesis, respectively. Moreover, the genotype of G2 had showed a bigger value and a relative stability for leaf area index compared to other genotypes in all the growth and developmental stages. Remarkable increase in dry matter accumulation pre valited during grain filling period in G2 genotype at the anthesis, double ridge and physiological maturity compared to other genotypes.

Relative growth rate indicated a decreasing trend during early to terminal growth stages under different water irrigation regimes. Besides, the negative effects of water deficit on relative growth rate at the reproductive (I3) and grain filling (I4) phases were more than vegetative stage (I2) which were concurred with the obtained values of leaf area index, crop growth rate and total dry matter at those stages. Therefore, the reduction of crop growth rate and accumulation of dry matter under water deficit conditions could be affected due to reduction in the relative growth rate values. The results of the present study concurred with previous findings of some workers due to positive relationship between relative growth rate and net assimilation rate for durum and bread wheat genotypes under water deficit conditions. it seems, severe decline of net assimilation rate during reproductive and grain filling phases compared to vegetative, was depended on higher reduction of leaf area index and crop growth rate at the post-anthesis which was caused consequently a sever reduction in the relative growth rate and total dry matter in the same phase.

Suitable condition had caused a significant increase in the leaf area index, which was enhanced contemporary percentage of the photosynthesis active radiation interception by plant canopy. Water limitation in early growth stage (I2) and grain filling (I4) was negatively reduced the photosynthesis active radiation interception in comparison to other irrigation regimes. Besides, negative effect of the early season water deficit on decreasing the photosynthesis active radiation interception had extended until the anthesis phase. Photosynthesis active radiation interception was decreased by 17%, 13% and 23% under water deficit treatment in the I2, I3 and I4 compared to optimum irrigation, respectively. Decreasing the photosynthesis active radiation interception during grain filling period was affected by early leaf senescence, pale and defoliation, which could express as well as reduction of the leaf area index, photosynthesis active radiation interception and finally crop growth rate under I4 water limitation treatment. The results indicated that G2 and G3 from anthesis to grain filling were shown the highest values for photosynthesis active radiation interception. It seems that lower reduction of the photosynthesis active radiation interception in G2 and G3 during grain filling has been related to similar results in the leaf area index growth parameter.

Regarding to linear relation between dry matter and photosynthesis active radiation interception, contemporary reduction in the accumulative photosynthesis active radiation interception and accumulative dry matter had stabled the radiation use efficiency under water deficit conditions by the plants. It seems that reduction of the intercepted radiation by plant canopy and decline of the dry matter accumulation under water deficit condition has been a self-regulating mechanism, which has decreased green leaf area, and leaf area index under moisture stress compared to optimum irrigation. Comparison of the linear slops between irrigation treatments with genotypic effects for radiation use efficiency revealed that impact of the water deficit on radiation

use efficiency was more than genotypic effect. In addition, with extension of the growth and developmental stages, linear slop in the water deficit treatments decreased compared to optimum condition, while there were no significant differences amongst genotypes for radiation use efficiency with advancing in different growth stages (Chapter 4).

The limited production of current photosynthetic assimilates during grain filling increases the contribution of the pre-anthesis assimilates stored in the stems, which are translocated to the sink tissues (mainly grain) under the water deficit conditions. Contribution of the pre-anthesis assimilates to grain is a physiologically complex process subjected to water stress during grain filling. The present results indicated that although the contribution of pre-anthesis assimilates to the grain increased during the one-leaf until grain filling period under water deficit conditions but both dry matter translocation and dry matter translocation efficiency decreased during the floral initiation to grain filling. The highest assimilate contribution was made under I3 water limitation condition while dry matter translocation and dry matter translocation efficiency exhibited the lowest values at those stage. Among genotypes studied, the G2 promising durum wheat and G3 bread wheat (Chamran) genotypes exhibited the maximum parameters due to remobilization. Particularly, the contribution of pre-anthesis assimilates to grain enhanced in the G2 genotype during the grain filing stage. It appears that higher growing degree-days (grater days to heading) and plant height under optimum moisture conditions could have an effect on enhancing stem carbohydrate reserves before the heading stage. On the other hand, the spike dry weight, spike harvest index and the spike-partitioning coefficient, as the plant sink capacity indices, indicated higher values in the G2 and G3 genotypes. Consequently, the strong source and sink and their balance in these genotypes improved remobilization and hence enhanced the contribution of pre-anthesis assimilates to grain during the grain-filling

period. In addition to this, the lower reduction in grain yield during grain filling under water deficit conditions observed in the G2 and G3 genotypes could be due to dominant remobilization traits in these genotypes (Chapter 5).

Developing drought tolerant varieties in arid and semi arid environmental conditions has been accepted as the most important factor for increasing crop potential, yield improvement and stability. Therefore, the identification of new genotypes and effective parameters with suitable advantages due to yield and their components is a fundamental challenge for wheat improvement programs under water deficit conditions. Accordingly, an investigation of the critical growth stages to drought stress in tolerant genotypes can help to overcome the negative effects of water deficit in different plants. In this study, it was observed that the responses of tillering traits in the promising durum wheat genotypes and bread wheat cultivar under optimum and water limitation conditions vary during the different growth and developmental stages, suggesting that tillering behavior depend on genetic factors and environmental conditions. It can be concluded that the one-leaf to the floral initiation was the most crucial growth stage for number of fertile tillers in both the durum and bread wheat genotypes under water deficit condition. The results also indicated that G5 durum genotype produced the lowest value for all the tillering traits under I2 irrigation regime treatment while Chamran bread wheat (G3) and G2 durum wheat genotypes exhibited the highest values for total number of tillers and number of fertile tillers. Interestingly, G2 showed similar tolerance to drought stress as shown by G3, which has been recognized as a drought stress tolerant cultivar, and can thus be classified a durum wheat drought tolerant genotype related to tillering behaviors.

The results of the present study also indicated that water deficit conditions during growth and developmental stages brought about different effects on the spike structure and its related traits in those studied genotypes. The number of spikelets per

spike, number of potential florets, spike length, spike dry weight, spike partitioning coefficient (SPC), and spike harvest index (SHI) significantly decreased under water deficit condition during the floral initiation to anthesis stage. In addition, the Chamran bread wheat cultivar (G3), which was used as a drought tolerant cultivar in the present study, showed the highest values for the number of spikelets, spike length, spike dry weight, spike partitioning coefficient and spike harvest index compared to the durum wheat genotypes. However, G2 durum wheat genotype (RASCON-37/ BEJAH-7) also exhibited higher values among the durum wheat genotypes. The significant relationships between the spike traits, the strongest correlation was shown between the spike harvest index (SHI) and spike-partitioning coefficient (SPC). Additionally, there were positive relationships between grain yield with number of spikelets per spike, spike length, spike dry weight and day to heading, total number of tillers, and finally number of fertile tillers. Overall, the results indicated that the most susceptible growth stage to water deficit was the floral initiation to anthesis stage in durum and bread wheat genotypes. Therefore, any moisture limitation during this period causes a negative effect on the spike structure, its related traits and grain yield.

The analysis of variance revealed that grain yield (GY), biological yield (BY), harvest index (HI), number of spike m^{-2}, number of grain per spike, 1000- grain weight (TGW), plant height and day to maturity were significantly affected under different irrigation regimes and genotype effects. The highest values due the grain yield, number of spike m^{-2}, number of grain per spike, plant height and day to maturity were produced under optimum irrigation. Hence, with inducing the water stress, there were significant decreases in their values. However, TGW, HI and maturity duration increased under I2 water deficit condition compared to optimum irrigation. On the other hand, the lowest plant height was produced under I2 while spike m^{-2} and grain $spike^{-1}$ with lowest values were belonged to I3 treatment. Moreover, it was observed that water deficit at the post

anthesis (I4) had caused a highest decrease in the grain yield, TGW, HI, day to maturity and maturity duration. Reduction of the maturity duration at the grain-filling phase reduced dry matter accumulation in the durum and bread wheat grains. It is probably reason for the decreasing TGW under the same treatment conditions. Overall, the severe decrease in the spike m^{-2} and grain $spike^{-1}$ under water limitation during floral initiation to anthesis stage and TGW at the grain-filling phase contributed to decrease of the grain yield and the HI under the terminal water deficit conditions.

With regard to importance of increasing water use efficiency (WUE) in crop production that is resulted in reducing stress on the ground water resources, agriculture must aim to improve all aspects of water management as well as developing crop cultivars with a higher efficiency of water utilization. In the present study, the level of water use efficiency was depended on the controlled ranges of soil water deficit at different stages. The highest amount of the water use efficiency was produced under I2 treatment based on biological and grain yield while the lowest value was made under I4 treatment. Water use efficiency obtained based on both the biological and grain yield gradually decreased with water limitation at the vegetative, reproductive and grain filling periods. The WUE was ranged based on grain yields 1.32, 1.07, 0.92 and 0.71 kg m^{-3} under I2, I3, I1 and I4 irrigation regime treatments, respectively. In addition, water limitation from one-leaf to floral initiation (I2) stage was improved the water use efficiency by 61 % (0.5 kg m^{-3}) compared to optimum irrigation. It was clear that increasing water use efficiency (based on grain yield) under early season water deficit was related to increase in stomatal resistance and reduction of water loss. However, grater extension of the plant roots under early season water deficit also has been caused better water use efficiency in this stage. Water use efficiency based on both grain and biological yield decreased under treatment I3 compared to I2, but it was exhibited higher value in comparison to optimum irrigation. Therefore, decreasing of the water

use efficiency during I3 compared to I2 treatment had been caused a severe competition between vegetative and reproductive organs to imbibe the available water by the plant. Hence, increasing the water use efficiency during this period using water management systems can cause decrease of the negative effects in water deficit at the plant growth and development. Regarding to the post anthesis stage, the lowest water use efficiency was belonged to I4 treatment in both biological and grain yield. It was shown the significant differences compared to optimum and water deficit treatments. Reduction in the biological yield under I4 treatment compared to I1 was related to reduce in grain yield. It has been well documented that water use efficiency is a function of available water for plant during grain filling (Richards 1996; Slafer and Araus 1998). With regard to genotypic differences that affects on water use efficiency in wheat, the results of present study indicated different trend for water use efficiency due to biological and grain yield. There was no significant difference among different durum and bread wheat genotypes due to water use efficiency based on biological yield whilst G3 and G2 genotypes had shown highest values (based on grain yield) for water use efficiency and significant differences compared to all the other genotypes (Chapter 6).

An understanding of the genetic and physiological basis of drought tolerance would facilitate the development of improved crop management and breeding techniques and lead to improved yield in unfavorable environments. In addition, identifying appropriate screening tools and quantifiable traits would facilitate the crop improvement process for drought tolerance. In this study the response of different durum and bread wheat genotypes evaluated using six physiological parameters, namely leaf relative water content (RWC), canopy temperature depression (CTD), leaf chlorophyll, proline content, stomatal conductance and photosynthetic rate, to the different irrigation regimes at different growth and developmental stages to distinguish between the drought tolerant and susceptible genotypes. The results have shown that the

effects of irrigation regime and genotype were highly significant (p <0.01) for leaf relative water content, canopy temperature depression, chlorophyll, proline content, stomatal conductance and photosynthetic rate during the different growth and developmental stages excepting for chlorophyll content at the soft dough stage. In addition to this, the interaction effects of the irrigation regime and genotype was highly significant at p <0.01 for the entire parameters evaluated excepting for stomatal conductance and photosynthetic rate at the booting stage.

The results showed that with advancement in the growth and developmental stages, the readings for leaf relative water content, canopy temperature depression, chlorophyll content, stomatal conductance and photosynthetic rate decreased under both optimum irrigation and water deficit conditions. In addition, water limitation during grain filling significantly decreased leaf relative water content, canopy temperature depression, chlorophyll content, stomatal conductance and photosynthetic rate at the soft dough stage. The biggest drop in leaf relative water content and canopy temperature depression at the booting and anthesis stage was dependent upon water limitation at the reproductive phase (I3). It is postulated that the decrease in leaf relative water content under water stress conditions disrupted water balance in the plants and consequently reduced stomatal conductance and photosynthetic rate. With increasing leaf temperature (and a concomitant decrease of CTD), as affected by reduction in leaf relative water content, both stomatal conductance and photosynthetic rate decreased.

Although with the advancement in growth and development, the leaf relative water content, canopy temperature depression, chlorophyll, stomatal conductance and photosynthetic rate in all genotypes decreased, the degree of reduction varied in the various genotypes studied. The genotypes, G2 (durum wheat) and G3 (Chamran bread wheat) both exhibited the highest leaf relative water content, canopy temperature depression, chlorophyll and proline accumulation, stomatal conductance and

photosynthetic rate readings under water deficit conditions compared to optimum irrigation. From these results, it can be concluded that the G2 durum wheat is a suitable genotype for cultivation under drought conditions, performing better, in several physiological aspects, than the established Chamran bread wheat drought tolerant cultivar and other durum wheat studied in present study (Chapter 7).

8.2 OVERALL CONCLUSION

The present study was undertaken in two phases to examine the physiological, agronomical, anatomical and biochemical variations in durum and bread wheat in response to different water deficit conditions. In the first phase, twenty promising genotypes of durum wheat (as shown in Appendix 3) were tested in a laboratory under optimum and different osmotic stress conditions using different concentration of poly ethylene glycol (PEG) for ranking their osmotic stress tolerance on the basis of GSTI and GSI. Durum wheat genotypes showed much variation in response to osmotic stress in term of germination percentage and rate, coleoptiles length, shoot length, root length, shoot dry weight, seedling dry weight, root to shoot length ratio and root to shoot dry weight ratio proved very helpful in categorize them. Four different genotypes based on their variation in drought tolerance, i.e., two osmotic stress tolerant (RASCON-39 / TILO-1 and RASCON-37 / BEJAH-7) and two osmotic stress sensitive (GARAVITO-3 / RASCON-37 // GREEN_8 and HAI-OU-17/ GREEN-38) were screened for further (field experiments) investigation.

The results of the laboratory and field experiments on the selected genotypes, at the germination and seedling stage (under different osmotic stress condition) were similar to those recorded field experimental condition (under different irrigation regimes) due to drought tolerance and susceptible. It was clear that there was a relationship between drought stress tolerance at the germination stage and other growth and development stages. Using germination tolerance indices at the germination stage, the drought tolerant genotype (G2) and susceptible genotypes (G1 and G5) were also the tolerant and susceptible genotypes in most of the morphological, agronomical, physiological, and biochemical characteristics studied. Consequently, it can be concluded that selections of drought tolerant varieties using germination tests can be

used to facilitate and accelerate breeding programs, which was one of the principle objectives of the present study.

During the first phase of the study, different osmotic stress conditions (- 0.3 to - 0.9 MPa) reduced all the germination traits except root to shoot length ratio and root to shoot dry weight ratio. The highest correlation coefficient among the different traits was seen between seedling dry weight and shoot dry weight. In addition, the highest and lowest GSTI values were observed in low (-0.3 MPa) and severe (-0.9 MPa) osmotic stress treatments. However, there was no difference between both GSTI and GSI indices in the tolerant genotypes.

In the second phase of the study, the results showed that with advancement in the growth and developmental stages LAI, CGR and PARI increased from one-leaf to anthesis, and thereafter gradually decreased during grain filling. Whereas RGR, NAR, RWC, CTD, chlorophyll content, stomatal conductance and photosynthetic rate indicated a decreasing trend with advancement in the growth and developmental stages under both optimum irrigation and water deficit conditions. It was observed that the responses of the physiological, agronomical and biochemical traits in the different genotypes were different under optimum and water deficit conditions during the growth and developmental stages. Water deficit has led to reduced values in physiological parameters, namely, LAI, CGR, RGR, NAR, PARI, RUE, RWC, CTD, accumulation of dry matter, dry matter translocation efficiency to grain, leaf chlorophyll content, stomatal conductance and photosynthetic rate. In addition, morphological factors such as spikelets per spike, potential florets, spike length, spike dry weight, number of spike m^{-2}, grain per spike, plant height, day to maturity, SPC, SHI and GY decreased under water deficit conditions, although the reduction in WUE was concomitant with water limitation at the reproductive and grain filling periods. On the other hand, water limitation at the vegetative phase (I2) increased TGW, HI, WUE and maturity duration.

Furthermore, proline accumulation in the leaves and the contribution of pre-anthesis assimilates to grain significantly increased under water deficit conditions compared to optimum irrigation. A severe decline in NARvalue during the reproductive and grain-filling phases compared to the vegetative phase was dependent on a higher reduction of LAI and CGR at the post-anthesis stage, which consequently caused a severe reduction in the RGR and total dry matter. Additionally, there were positive relationships between grain yield with number of spikelets per spike, spike length, spike dry weight, day to heading, total and fertile tillers.

The final results also revealed that both genotypes G2 and G3 achieved higher values for LAI, CGR, PARI, RUE, SHI, SPC, WUE, RWC, CTD, dry matter accumulation, remobilization parameters, spike dry weight, total and fertile tillers, spikelets per spike, spike length, chlorophyll content, proline accumulation, stomatal conductance and photosynthetic rate under water deficit conditions compared to the other genotypes. In addition, the study of the drought tolerant and susceptible indices and their correlations with grain yield also confirmed that amongst the drought tolerant indices, which were used to estimate the highest desirable drought tolerance genotypes, the stress tolerance index (STI) was the best trait for screening genotypes under optimum irrigation and different water deficit conditions. Moreover, the most tolerant genotype in the different water deficit conditions were the Chamran bread wheat (G3) and G2 durum wheat genotypes, which were screened based on stress susceptibility index (SSI), stress tolerance index (STI), tolerance index (TOL), mean productivity (MP), geometric mean productivity (GMP), yield reduction ratio (Yr) and relative performance (PR).

Based on similar results obtained for tolerant and susceptible genotypes using stress tolerance index under laboratory (germination and seedling stage) and field conditions, this trait might be used as a reliable drought selection criterion instead of

field screening for drought tolerance at a large scale, thus saving on experimental costs. From the experimental results, it can be concluded that the G2 durum wheat might be a suitable genotype for cultivation under stress drought conditions, performing similar, in several ecophysiological aspects in compared to the established Chamran bread wheat drought tolerant cultivar and better traits than other durum wheat genotypes employed in the present study.

1.4 PUBLICATIONS

The results presented in this thesis have been published or submitted for publication in the following articles:

Chapter 3:

Moayedi, A.A and Barakbah, S.S. 2007. Study on Durum Wheat Genotypes at Germination Stage under Different Osmotic Stress. *In: Proc.eeding of Agriculture is a Business. ISSAAS Congress 2007, Malaysia*, pp: 23-24.

Boyce, A.N., Barakbah, S.S., Moayedi, A.A. and Ghodsi, M. 2009. Effect of Different Osmotic Stress on Percentage, Rate and Germination Stress Index in Durum Wheat Genotypes. *In: Proc.eeding of EKSPO Inovasi 2009, Malaysia*, pp: 27-28.

Moayedi, A.A., Boyce, A.N., Barakbah, S.S. 2009. Study on Osmotic Stress Tolerance in Promising Durum Wheat Genotypes Using Drought Stress Indices. *Research Journal of Agriculture and Biological Sciences* **5**: 603- 607.

Boyce, A.N., Barakbah, S.S., Moayedi, A.A. and Ghodsi, M. 2009. Susceptibility of Durum Wheat Genotypes at Germination Stage under Different Osmotic Stress. *In: Proc.eeding of EKSPO Inovasi 2009, Malaysia*, pp: 27-28.

Moayedi, A.A., Boyce, A.N., Barakbah, S.S. and Ghodsi, M. 2009. The Effects of Different Levels of Osmotic Stress on Germination and Seedling Growth in Promising Durum Wheat Genotypes. *Middle Eastern and Russian Journal of Plant Science and Biotechnology* **3:** 10-14.

Moayedi, A.A and Boyce, A.N. 2009. Study on Osmotic Stress Tolerance in Promising Durum Wheat Genotypes Using Drought Stress Indices. *In: Proc.eeding of Tropical Agriculture in a Changing Climate and Energy Scenario 2009*. Selangor, Malaysia.

Chapter 4:

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Chapter 5:

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APPENDICES

APPENDICES

Appendix 1 Physico-chemical characteristics of field soil in Mashhad, Iran

Depth (cm)	PH	EC (ds m-1)	SP (%)	Soil texture (%)			
				Sand (2-0.05 mm)	Silt (0.05-0.002 mm)	Clay (<0.002 mm)	Gravel (>2 mm)
0-30	8.1	1.80	40.5	31.4	52	16.6	-
30-75	8.1	2.55	33.8	35.4	45	19.6	-
75-150	8.2	0.85	23.7	86.4	8	5.6	>75

Appendix 1 (cont.)

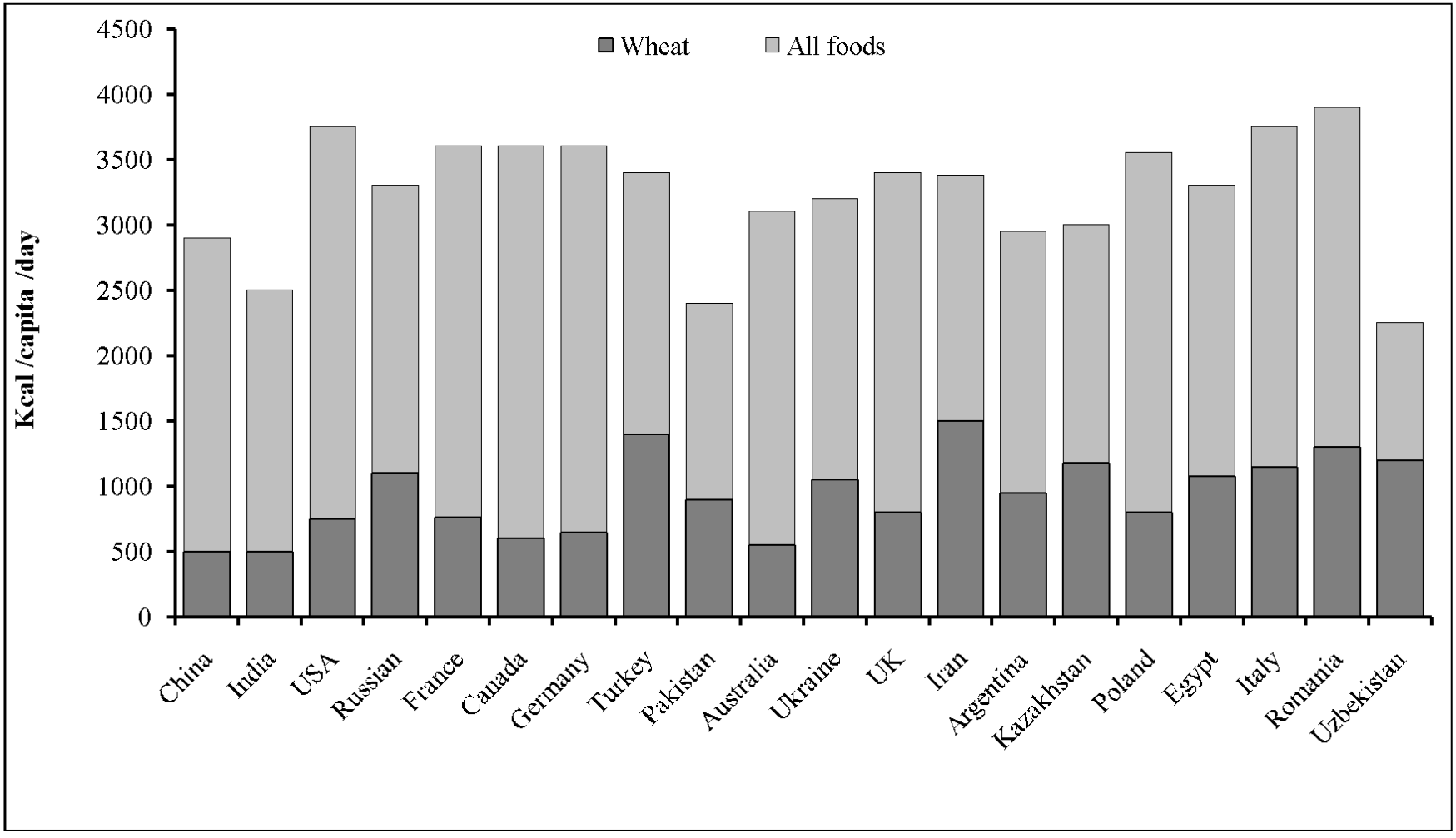
Depth (cm)	OC (%)	N (%)	P (mg kg-1)	K (mg kg-1)	Neutral (%)	CEC	SAR
0-30	1.0	0.10	20.8	370.5	14.2	12.8	2.4
30-75	0.19	0.03	10.4	156	23.2	8.6	3.3
75-150	0.03	0.02	12.8	117	11.0	5.8	1.8

Appendix 2 Climatology information during 2007-2008 in Mashhad, Iran

Mount	Temperature (°C)			Rainfall (mm)	Moisture (%)
	Max	Min	Average		
November	22.4	-0.2	9.8	17.5	68
December	16.8	-8.2	3.6	26.5	75
January	8.8	-21	1.2	25	78
February	19.6	-13.6	1.2	22.2	70
March	30	0.8	15.8	4.1	43
April	34	5.4	17.8	21.6	47
May	35	10.6	21.5	22.6	44
June	40.6	11.8	27.1	0	31

Appendix 3 List of durum wheat genotypes used in germination experiments (laboratory)

Genotype	Pedigree	Genotype	Pedigree
G1	ARIA	**G11**	GREEN_2/HIMAN_12
G2	PISHTAZ	**G12**	HUI/YAV79//RASCON_37
G3	STOT//ALTAR 84/ALD	**G13**	LIRO_3/LOTAIL_6
G4	RASCON_39/TILO_1	**G14**	MUSK_1//ACO89/FNFOOT_2
G5	E90040/MFOWL_13//LOTAIL_6	**G15**	CADO/BOOMER_33
G6	BRAK_2/AJAIA_2//SOLGA_8	**G16**	PLATA_3//CREX/ALLA/3/LOTAIL_6
G7	HAI-OU_17/GREEN_38	**G17**	GARAVITO_3/RASCON_37//GREEN_8
G8	SN TURK MI83-84 375/NIGRIS_5//TANTLO_1	**G18**	BOOMER_18/KITTI_1//LUND_4
G9	RAFI97/RASCON_37//BEJAH_7	**G19**	CPAN.6018/2*RAJ1555//2*PORRON_4
G10	RASCON_37/BEJAH_7	**G20**	HYDRANASSA30/SILVER_5//SILVER_3/RISSA



Appendix 4 Share of wheat in food consumption in selected countries. Source: FAOSTAT (2007) and Dixon *et al.* 2009

Appendix 5 Analysis of variance (ANOVA) for the different characteristics of durum wheat genotypes during germination and the seedling stages

Characters	Source of variation(Mean Square)				
	Osmotic stress	Genotype	Osmotic stress × Genotype	Error	CV %
Germination percentage (G %)	8.611**	0.149**	0.049**	0.049	18.10
Germination rate (GR)	0.211 **	0.010 **	0.002 ^{ns}	0.004	17.48
Coleoptiles length (mm)	97.143 **	0.188 *	0.169 *	0.107	13.64
Shoot length (cm)	1106.51**	1.494 ^{ns}	1.527^{ns}	1.140	18.72
Root length (mm)	450.980 **	1.618 *	1.018 ^{ns}	0.836	17.60
Shoot dry weight (mg)	1111.11**	3.137 ^{ns}	2.614 ^{ns}	2.496	18.13
Root dry weight (mg)	826.39**	4.017 *	2.533 ^{ns}	2.291	21.89
Seedling dry weight (mg)	36.68.23**	10.71 ^{ns}	7.826 ^{ns}	7.534	20.87
Root / Shoot length	171.77**	1.28 ^{ns}	2.531*	1.595	24.42
Root / Shoot dry weight	129.06**	2.77 ^{ns}	2.82 ^{ns}	2.104	22.78
Degrees of freedom (df)	3	19	57	160	-

* Significant difference at $P < 0.05$ ** significant difference at $P < 0.01$ *ns*: no significant

Appendix 6 List of durum and bread wheat genotypes used in field experiments

Entry	Genotype	Pedigree	Plant height (cm)	1000KW (g)	Spike length (mm)
G1	durum wheat	HAI-OU-17/ GREEN-38	85	50	61
G2	durum wheat	RASCON-37/ BEJAH-7	87	54	62
G3	bread wheat	CHAMRAN	85	49	83
G4	durum wheat	RASCON-39/TILO-1	87	54	61
G5	durum wheat	GARAVITO3/ RASCON37// GREEN8	83	53	62

Appendix 7 Analysis of variance (ANOVA) for cumulative dry matter (CDM) during growth and developmental stages

Variation sources	df	Mean square (MS)						
		Two-leaf	Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
Replication	2	24.5^{ns}	681^{ns}	378^{ns}	12.69^{ns}	10734^{ns}	11467.4^{ns}	9324^{ns}
Irrigation regime (I)	3	81.4^{ns}	7641^{**}	37454^{**}	232776^{**}	291629^{*}	450873^{**}	761939^{**}
Error	6	192.4	615	542	1698.9	39064	7000.8	7306.9
Genotype (G)	4	208^{ns}	4443^{**}	4999^{**}	2755^{ns}	5396.9^{ns}	4998.4^{ns}	2561^{ns}
I ×G	12	169^{ns}	1483^{**}	1301^{**}	185446^{ns}	5931.6^{*}	7395.3^{ns}	$3569.^{ns}$
Error	32	94.1	399	406.7	1254.6	2762	3035.3	3382.4
CV %	-	10.55	9.94	6.25	5.76	5.69	5.20	4.83

* Significant difference at $P < 0.05$ ** significant difference at $P < 0.01$ *ns*: no significant

Appendix 8 Analysis of variance (ANOVA) for leaf area index (LAI) during growth and developmental stages

Variation sources	df	Mean square (MS)						
		Two-leaf	Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
Replication	2	0.04^{ns}	0.04^{ns}	3.17^{ns}	0.07^{ns}	0.10^{ns}	0.40^{ns}	0.63^{ns}
Irrigation regime (I)	3	1.014^{***}	1.01^{***}	0.29^{ns}	0.25^{***}	0.75^{***}	2.70^{*}	1.31^{*}
Error	6	0.022	0.02	0.08	0.02	0.02	0.43	0.32
Genotype (G)	4	0.199^{ns}	0.199^{***}	0.04^{ns}	0.67^{***}	0.93^{***}	1.39^{***}	1.27^{***}
I ×G	12	0.015^{ns}	0.01^{ns}	0.06^{ns}	0.29^{***}	0.47^{***}	0.44^{***}	0.46^{***}
Error	32	0.012	0.012	0.05	0.05	0.04	0.12	0.13
CV %	-	14.620	8.620	10.04	6.66	13.24	26.25	14.5

* Significant difference at $P < 0.05$ *** significant difference at $P < 0.01$ ns: no significant

Appendix 9 Analysis of variance (ANOVA) for crop growth rate (CGR) during growth and developmental stages

Variation sources	df	Mean square (MS)					
		Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
Replication	2	3303.8^{ns}	2285^{ns}	4798^{ns}	42955^{ns}	6126^{ns}	2046^{ns}
Irrigation regime (I)	3	52756**	205117**	236065**	388288**	545120**	430530**
Error	6	5069	2744	13606	101092	25674	26107
Genotype (G)	4	23657**	968^{ns}	35616**	9377^{ns}	9894^{ns}	4359^{ns}
I×G	12	6448**	5922^{ns}	8421^{ns}	20158^{ns}	32216*	10070*
Error	32	1789	3473	6332	11899	15350	4354
CV %	-	1371	11.61	10.97	11.07	17.35	17.86

* Significant difference at $P < 0.05$ ** significant difference at $P < 0.01$ *ns*: no significant

Appendix 10 Analysis of variance (ANOVA) for relative growth rate (RGR) during growth and developmental stages

Variation sources	df	Mean square (MS)					
		Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
Replication	2	0.034 ^{ns}	0.116 ^{ns}	0.020 ^{ns}	0.081 ^{ns}	0.253 ^{ns}	0.024 ^{ns}
Irrigation regime (I)	3	1.095 ^{ns}	0.711 *	0.381 *	0.027 ^{ns}	0.760 ^{ns}	0.205 ^{ns}
Error	6	0.264	0.096	0.049	0.064	0.335	0.057
Genotype (G)	4	0.246 **	0.183 ^{ns}	0.149 **	0.008 ^{ns}	0.024 ^{ns}	0.021 ^{ns}
I×G	12	0.074 ^{ns}	0.205 *	0.48 ^{ns}	0.021 ^{ns}	0.059 ^{ns}	0.005 ^{ns}
Error	32	0.049	0.078	0.027	0.015	0.032	0.011
CV %	-	8.361	8.630	9.73	9.392	6.632	22.72

* Significant difference at $P < 0.05$ ** significant difference at $P < 0.01$ *ns*: no significant

Appendix 11 Analysis of variance (ANOVA) for net assimilation rate (NAR) during growth and developmental phases of durum and bread wheat genotypes under different irrigation regimes

Variation sources	df	NAR mean square (MS)					
		Double ridge	Terminal spikelets	Booting	Anthesis	Soft dough	Physiological maturity
Replication	2	1635 ^{ns}	46144 *	941 ^{ns}	3472 ^{ns}	12774 ^{ns}	7113 ^{ns}
Irrigation regime (I)	3	28304 *	26687 **	16379 **	12362 *	189303 **	48387 *
Error	6	1433	1218	986	6254	5390	5332
Genotype (G)	4	58075 **	1986 ^{ns}	8396 **	4241 *	5235 *	2881 ^{ns}
I×G	12	4550 ^{ns}	3144 ^{ns}	2289 **	3006 *	3858 *	4315 *
Error	32	3921	2249	6695	1117	1756	1584
CV %	-	23.96	19.16	1179	1391	1916	26.01

* Significant difference at $P < 0.05$ ** significant difference at $P < 0.01$ *ns*: no significant

Appendix 12 Analysis of variance (ANOVA) for photosynthesis active radiation interception (PARI), radiation extinction coefficient (k) and radiation use efficiency (RUE) at the different growth and developmental phases

Mean square (**PARI** %)								
Variation sources	df	DR	TS	Booting	Anthesis	SD	PM	k
Replication	2	35.4**	63.4**	97.4**	135.2*	153.6**	209.8*	0.002
Irrigation regime (I)	3	197.5**	217.4**	364.2**	787.9**	1043**	799.6**	0.081*ns*
Error	6	2.8	4.4	11.8	16.1	9.4	36.1	0.042
Genotype (G)	4	58.1**	79.1**	81.4**	212.3**	48.1*	270.7**	0.095*ns*
I×G	12	109.9**	123.5**	165.2**	365.3**	30.4*	173.8**	0.05 *ns*
Error	32	5.4	6.5	8.35	24.3	14.3	16.2	0.004
CV %	-	6.98	7.58	7.69	6.63	6.99	7.87	6.73

* Significant difference at $P < 0.05$ ** significant difference at $P < 0.01$ *ns*: no significant

Appendix 13 Analysis of variance for dry matter translocation (DMT), dry matter translocation efficiency (DMTE), contribution of pre-anthesis to grain (CPAA), spike dry weight (SPKDW), total tillers, fertile tillers and tiller survival percentage in durum assimilates and bread wheat genotypes under different water deficit conditions.

Variation sources	df	Mean square (MS)						
		DMT (mg plant^{-1})	DMTE (%)	CPAA (%)	SPKDW (mg plant^{-1})	total tillers	fertile tillers	Tiller survival (%)
Irrigation regime (I)	3	679823*	945**	2420**	21476**	0.547***	2.804^{ns}	4592.16***
Error	6	6425	7.45	30.2	26.6	0.233	0.054	60.54
Genotype (G)	4	389225*	520**	723.6**	5222**	1.236*	0.863*	575.22*
I×G	12	38199^{ns}	97.8**	223.3**	200^{ns}	1.159	0.547	127.38
Error	32	6322	5.8	29.2	6075	0.144	0.032	37.37
CV %	-	11.42	9.80	8.52	6.95	12.22	13.22	14.33

*Significant difference at P <0.05; ** significant difference at P<0.01; ns: Not significant

Appendix 14 Analysis of variance (ANOVA) for number of spikelets spike^{-1} (SPKE), number of total florets (NTF), number of potential florets (NPF), spike length (SPKL), spike dry weight (SPKDW), day to heading (DH), spike partitioning coefficient (SPC), spike harvest index (SHI) in durum and bread wheat genotypes under different irrigation regimes.

		Mean square (MS)							
Source of variations	df	SPKE	NTF	NPF	SPKL(mm)	SPKDW(mg)	DH	SPC (%)	SHI (%)
Replication	2	0.2	11.5	3.3	29.1	15.39.4	6.21	5.74	1.95
Irrigation (I)	3	1.8*	68.2^{ns}	96.4***	66.1*	10803***	93.2*	64.3***	34.5***
Error	6	1.6	38.3	9.7	12.6	20.5	17.2	1.29	0.65
Genotype(G)	4	7.7***	684.8***	228***	1728.2***	2522***	33.2*	15.8***	15.4***
I×G	12	1.4*	112.9***	47.4*	38.9***	97.4^{ns}	3.9^{ns}	3.6***	4.2***
Error	32	0.7	17.23	29.7	12.6	56.11	10.2	0.98	0.62
CV %	-	5. 4	5. 05	10. 21	5. 2	6. 40	4.73	10.7	10.97

*Significant difference at $P < 0.05$ ***significant difference at $P < 0.01$ *ns*: no significant

Appendix 15 Analysis of variance for biological yield (BY), grain yield (GY), no. spike m-2 (SPKN), no. grain spike-1 (GN), 1000-grain weight (TGW), harvest index (HI), plant height (PLH), day to maturity (DMA) and maturity duration (MD) of the durum and bread wheat genotypes under different water deficit conditions

Source of variations	df	Mean square (MS)								
		BY (th^{-1})	GY (th^{-1})	SPKN	GN	TGW (g)	HI (%)	PLH (cm)	DMA	MD
Replication	2	4.65	0.3	752.2	13.9	7.24	2.3	161	11.3	26.2
Irrigation (I)	3	28^{ns}	59.8^{***}	90388^{***}	227^{***}	1830^{***}	2123^{*}	584^{***}	320^{***}	711^{***}
Error	6	0.9	0.1	613.7	43.3	0.21	4.2	35	10.6	12.3
Genotype(G)	4	12^{*}	2.4^{*}	59151^{***}	1193^{***}	261^{***}	144^{*}	64.2^{***}	93.3^{***}	13.6^{ns}
I×G	12	5.9^{ns}	0.9^{*}	8718^{***}	479^{***}	16.1^{*}	41^{ns}	17.2^{***}	21.8^{ns}	16.3^{ns}
Error	32	1.5	0.2	621.9	42	0.70	5.4	16.4	10.3	18.7
CV %	-	8.17	8.02	6.67	12.87	11.94	6.6	4.98	6.1	11.5

* Significant difference at $P < 0.05$ *** significant difference at $P < 0.01$ *ns*: no significant

Appendix 16 Analysis of variance (ANOVA) on water use efficiency based on biological and grain yield

Variation sources	df	Mean square (MS)	
		WUE (Biological yield)	WUE Grain yield
Irrigation regime (I)	3	2.140**	1.115**
Error	6	0.016	0.001
Genotype (G)	4	0.011ns	0.302**
I ×G	12	0.292**	0.028**
Error	32	0.017	0.003
CV %		4.65	5.31

** significant difference at $P < 0.01$ *ns*: no significant

Appendix 17 Analysis of variance (ANOVA) for canopy temperature depression (CTD) and leaf relative water content (RWC) during different growth and developmental stages

Variation sources	df	Mean square (MS)					
		canopy temperature depression			leaf relative water content		
		Booting	Anthesis	soft dough	Booting	Anthesis	soft dough
Irrigation regime (I)	3	40.10**	2.93**	22.71**	798.3**	30.87.8**	1161**
Error	6	0.25	0.10	0.16	9.47	11.51	27.16
Genotype (G)	4	2.62**	1.03**	5.67**	125.5**	123.7**	75.1**
I ×G	12	1.14**	0.97**	1.23**	115.5**	116.14**	42.47**
Error	32	0.36	0.14	0.15	11.51	11.46	6.59
CV %	-	8.46	6.82	11	4.92	5.56	4.67

** indicates significant difference at $P < 0.01$

Appendix 18 Analysis of variance (ANOVA) for chlorophyll content (SPAD unit) and Proline concentration during different growth and developmental stages

Variatio sources	df	Mean square (MS)			
		chlorophyll content (SPAD)			Proline concentration
		Booting	Anthesis	Soft dough	
Irrigation regime (I)	3	15.59*	57.79***	109.58^{ns}	8.19***
Error	6	3.26	2.80	52.73	0.006
Genotype (G)	4	37.67***	32.57***	11.55^{ns}	2.35***
I ×G	12	15.18***	20.12***	18.81^{ns}	1.35***
Error	32	2.23	2.49	11.40	0.035
CV %	-	3.29	3.39	9.10	8.62

$_{*}$ indicates significant difference at $P < 0.51$ $_{**}$ indicates significant difference at $P < 0.01$

Appendix 19 Analysis of variance (ANOVA) for stomatal conductance and photosynthesis rate during different growth and developmental stages

Treatment		Mean square (MS)					
		Stomatal conductance			Photosynthesis rate		
	df	Booting	Anthesis	Soft dough	Booting	Anthesis	Soft dough
Irrigation regime (I)	3	2.66**	0.437**	0.609**	396.31**	95.017**	85.083**
Error	6	0.015	0.006	0.010	1.553	4.163	1.267
Genotype (G)	4	0.029*	0.865**	1.053**	27.14**	59.702**	65.801**
I ×G	12	0.018^{ns}	0.149**	0.232**	1.220^{ns}	15.871**	13.210**
Error	32	0.009	0.027	0.27	1.529	2.997	3.137
CV %		6.16	16.60	26.34	9.09	15.08	24.35

* indicates significant difference at $P < 0.51$ ** indicates significant difference at $P < 0.01$